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REMOVAL OF ALGAE IN NATURAL BODIES OF WATER

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ABSTRACT

Floating blue-green algae predominate in Clear Lake during most of the algal growing season. They are subject to concentration by gentle winds which can drive intense concentrations of algae into relatively small areas. Algal concentrations in these scums may vary between 1000 mg and 20,000 mg per liter surface water (1 cm to 5 cm deep). Because of this natural flotation and wind-induced concentration only about 2 percent of Clear Lake's surface need be skimmed throughout the algal growing season to decrease the average level of floating algae in the lake.

Annual costs of building and operating a single skimming station would be about $50,000 to $60,000 (1974 dollars). The benefits derived by removing nuisance algal scums should support three skimming stations. If an annual harvest of 5000 tons algae brought $100 per ton, up to 7 skimming stations could be supported. The annual costs of removing nutrients by surface skimming would be about $1.90 to $2.40 per kg nitrogen or $15 to $19 per kg phosphorus removed if three stations harvested 1000 tons algae annually. Tests have shown that the blue-green algae which predominate in Clear Lake can be concentrated using mechanical straining techniques. However, the first two algal pickup units tested did not perform satisfactorily. New information on algal scum characteristics has been incorporated into the design of a third pickup unit (The U.C. Surface Skimmer) which is now being constructed. Testing and evaluation of the unit will be conducted in Clear Lake. The economic analysis presented herein is contingent upon the successful functioning of this unit.

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SECTION I

SUMMARY AND CONCLUSIONS

Clear Lake, California is a 17,000 hectare surface area, 9-meter average depth eutrophic lake located in Lake County about 130 kilometers north of San Francisco, California. Some of the water in the lake is used for irrigation in Yolo County but because of its proximity, productivity and natural beauty, the lake is heavily used for boating, fishing and other forms of aquatic recreation. The lake's water quality is excellent but at times impaired by floating micro-blue green algae which appear to be removable by skimming or related mechanical activity. Because of these factors, Clear Lake has been utilized as a model system for our studies of the feasibility and cost of direct removal of floating micro-algae.

During the winter rains of each year, flood waters enter and accumulate in Clear Lake. These flood waters bear hundreds of tons of soluble nitrogen compounds such as nitrate, nitrite and ammonium and organic nitrogenous materials in both soluble and insoluble form. Also associated with the flood waters and the sediment transported into the lake are many tons of soluble and adsorbed phosphorus compounds, and trace minerals essential for algal growth.

The physical properties of Clear Lake are such that it is an ideal algal growth unit. Because it is shallow, it tends to warm quickly in the spring. Due to a combination of high surface temperatures and frequent wind mixing, Clear Lake tends to stratify and destratify periodically throughout the late spring, summer and early fall. Under these conditions, algae tend to grow profusely. Periodic crops of algae grow and die. Many of the algae settle to the bottom adding putrescible organic matter to the bottom muds. Putrescible muds at the bottom of the lake are then intermittently subjected to oxygenation, which impairs the methane bacteria that normally transform organic acids to methane, and low oxygen levels which favor the production and buildup of organic acids within the muds. As they accumulate, organic acids, in turn, tend to dissolve and release combined forms of nitrogen and phosphorus. Release is often followed by diffusion or mechanical transport of the materials into the upper waters through disturbance of the muds by gas bubbles that continuously emit from deeper sediments and through wind mixing and suspension of sediments and associated soluble constituents. Surface waters are thus enriched with ammonium and orthophosphate forms of nitrogen and phosphorus available for microbial growth.

According to the available data, nitrate tends to accumulate and increase in concentration in the lake waters during the winter due to flood inputs and probably bacterial oxidation of ammonium to nitrate. According to 1969 data, as the lake warmed in spring to about 15°C, nitrate began to dissappear from the system more quickly than could be accounted for by algal growth. Accordingly it appears that bacterial reduction of nitrate or denitrification occurs in the lake during the later spring, leading to the low nitrate concentrations observed at that time. As summer progressed, an abundance of phosphate and a dearth of nitrate seemed to favor the growth of nitrogen fixing blue-green algae. According to Horne(13) who has observed nitrogen fixation in Clear Lake since 1970, as much as 500 metric tons of nitrogen has been fixed in Clear Lake in a single season by nitrogen fixing Aphanizomenon and Anabaena.

Because of flood transport, recycle and nitrogen fixation, the average nutrient concentration in Clear Lake is such that about 19 milligrams per liter (mg/l) or about 27,000 metric tons of algae could be grown in the lake's water before some nutrient became limiting to algal growth. However, because of light limitations by wind-induced suspension of clay turbidity and because of light absorption by the algae themselves, the algal growth potential of the lake is only fractionally exerted and the maximum average standing biomass was found by Gaonkar(10) to be only 10 mg/l or about 14,000 metric tons. Frequently Gaonkar found the biomass of algae present in the lake to be less than 5,000 metric tons. While it is not possible to accurately predict from the existing data how much algae will be available for skimming each year, it is expected to vary between 1,000 and 5,000 metric tons.

As noted previously, floating blue-green algae available for skimming apparently predominate in Clear Lake because turbidity often deters the penetration of sufficient light to support the growth of algae which are strictly planktonic, and because special nutrient conditions favor nitrogen fixing blue greens. Because of their normal position at or near the lake surface, floating blue greens are subject to trapping in the surface film and death by overillumination or overheating. They are also subject to concentration by gentle winds which may drive intense concentrations of algae into relatively small areas along the lake shores. Concentrations of algae in the wind driven scums have been found in this study to vary from 1,000 to 20,000 mg/l of surface water (1 to 5 cm deep) depending on the location in the lake and the total amount of algae which have drifted in. Concentrations of 1,000 to 20,000 mg/l constitute magnification factors of 100:1 to 2000:1 compared with the average biomass concentration of 10 mg/l in the lake. It is this natural floatation and wind induced concentration that makes skimming a potentially feasible and cost-effective method for removal of algae and associated nutrients from Clear Lake.

Based on frequently observed natural concentration factors of 100:1, it appears likely that about 2 percent of the lake's surface would need to be skimmed to temporarily remove a major part of the scum problem. However, as the scum is removed, new scum would probably form and hence continual skimming would probably be required throughout the growing season in order to decrease the average level of floating algae in the lake. Once skimmed and removed, the algae would not be available to settle and undergo acid fermentation with attendant phosphate and ammonium release. However, the overall impact of removing 1000 to 5000 metric tons of algae may be too small to fundamentally effect the ecology of Clear Lake.

In spite of their tendency to collect in the surface layer of the lake, the Clear Lake algae, in common with most micro-algae, are highly hydrophilic and are initially repelled by intrusive surfaces. Accordingly inclined planes and similar devices which have been employed to lift oil from a water surface do not work on algae with dependable continuity. This has led to the conclusion that effective removal of surface micro-algae requires development of a device or pickup unit which isolates and concentrates the surface growing algae with a minimum of disturbance of the surface prior to lifting. Once isolated within the pickup unit, the algae can be pumped for concentration by screening and dewatering on sand beds. The processes of concentration of algae by screening and dewatering on sand beds are well known but more data is required for determining the degree of concentration attainable with various types of strainers in series with a functional pickup unit and pump. The pickup unit itself must be a hydraulically analagous model of the system. Accordingly a full scale skimming pickup unit must be constructed and tested in order to study a given pickup system. A new model of such a pickup device has been designed and modeled on the basis of all facts determined in this project thus far. However, this key unit has not yet been constructed and tested on a large scale.

If one assumes a pickup unit has been perfected, it is then possible to make an economic analysis of the system. To establish a single, permanent harvesting station at Clear Lake will require capital investment in the range of $120,000 to $150,000 (1974 dollars) depending on whether a 1.5 meter or 7.6 meter pickup element is used. A 1.5 meter wide pickup unit appears to be most efficient since it can work close to the lake shore where the most dense concentrations of floating algae are to be found. On the other had, a 7.6 meter unit might be required to cover significant areas of large lakes.

Assuming an effective pickup system is perfected, locations at Clear Lake or other lakes repeatedly troubled with algal scums could construct permanent skimming stations to control the scums on a continuing basis. If this is done it may be feasible to also install algal fermentation systems to produce methane gas for use in operating the system or for other useful purposes. Again, assuming a pickup device can be perfected, annual costs of building and operating a single skimming station should be about $50,000 to $60,000 (1974 dollars).

In the case of Clear Lake, it is estimated that successful removal of nuisance scums of algae should bring a benefit of at least $200,000 (1974 dollars) per year to the overall lake in the form of increased property values and increased visitor days. Thus, overall benefits should support the operation of about three skimming stations. If a market or use can be worked out for the algae removed, the net cost of skimming may be decreased in proportion to the value realized from the algae. If more than three skimming stations are needed, algae sales or other benefits will probably be required to maintain a benefit cost ratio greater than one. However, specific local benefits would have to be examined in each case. If as much as 5,000 metric tons of algae could be removed each year by skimming and if the likely value of $100 per metric ton could be obtained for algae, the removal stations could be economically self supporting up to a limit of about 7 stations. On the other hand, as noted above, if the yields of algae are less than 1,000 metric tons per year and no value is found for the algae, only about 3 stations could be supported by estimated benefits.

If the minimum yield of 1,000 metric tons of algae per year is obtained, the cost of removing nitrogen by surface skimming could be as high as $1.90 to $2.40 per kilogram of nitrogen removed, and the cost of removing phosphorus by surface skimming could be as high as $15 to $19 per kilogram of phosphorus removed. On the other extreme, if 5,000 metric tons of algae are produced and sold, the operation could be a profitable enterprise. The former costs appear extremely high and should encourage research into means of preventing the intrusion of nitrogen and phosphorus into the lake. On the other hand, the possibility that a cost effective means will be found to prevent the intrusion of flood-borne nutrients into Clear Lake or other natural bodies of water appears unlikely. Accordingly, regardless of whether or not it is economical in a specific case, skimming should be perfected as a fail safe method of controlling algal scums. The fact that it may be cost effective under certain circumstances only adds motivation for its perfection. Accordingly the major recommendation of this report is that research should continue until a pickup device is perfected.

The unique problems of intermittent and undependable scum occurrence and logistics should be carefully considered in future budget planning.

Experiments to perfect a skimming device are currently continuing under modest sponsorship by the Lake County Board of Supervisors administered through the Lake County Flood Control and Water Conservation District and the University. Current funds are only adequate however, to construct and test one model of a specific skimming device. Should this device prove encouraging, a supplementary report of its performance will be filed with the sponsoring agencies, together with proposals for continued monetary support.

SECTION II

INTRODUCTION

PURPOSE AND SCOPE

It is the purpose of this report to summarize the research accomplished to date on a project entitled "Removal of Algae in Natural Bodies of Water" (RAINBOW). This project was initiated June 1, 1969 and after several no-cost extensions terminated October 1, 1974.

The project scope was to develop a means of removing floating micro-algae from the surface of lakes, to predict the cost of removal of such algae in terms of capital and operation and maintenance cost per unit volume processed, and cost per unit weight of algae removed. To be included was a cost-benefit analysis including the value of algae removed and possible increases in property value due to their removal. Also to be studied was the projected effect of direct algae removal on the process of eutrophication.

PROJECT HISTORY

Previous studies by Oswald and Golueke (1) at the Sanitary Engineering Research Laboratory of the University of California, Berkeley has shown that micro-algae growing on sewage could be harvested from the waste stream at a cost of approximately $5 per million liters of water processed and that this cost was essentially independent of algal concentration. These encouraging experimental results, together with an increased national awareness of the problem of cultural eutrophication of lakes led to the concept of direct removal of nuisance algae from problem lakes and to this project.

At the time of initiating the project there was also in progress development by E.P.A. of a bio-assay procedure (later termed "Algal Assay

Procedure") for rapid practical determination of the potential of dissolved nutrients in a body of water to support a measurable level of algal growth (2). These techniques were incorporated and employed in this project to explore the phenomenology of interplay of algal growth and algal growth potential in a real body of water. Because of its problems with eutrophication and occasional algal scums and because of the great interest in it as a conveyance channel for water from the projected Middle Fork, and Eel River dams to the Sacramento River, Clear Lake was chosen as the body of water for study. Clear Lake was also an advantageous body for study because it had been the subject of several prior water quality studies and at that time was the subject of ongoing studies supported by the California State Department of Water Resources (1) the U.S. Department of Interior, Geological Survey(3), and the Lake County Flood Control and Water Conservation District(4). These studies and the current study were coordinated through many consultations and advisory board meetings among the groups conducting the various studies. Eventually these meetings together with strong local interest gave rise to the Clear Lake Water Quality Council Inc., a non-profit organization dedicated to the improvement of water quality in Clear Lake. The Clear Lake Water Quality Council in turn has appointed a Research Advising Board to review and encourage future research on Clear Lake problems.

In staffing the Joint University FWPCA project, Suresh Gaonkar, a Ph.D. candidate and graduate student interested in the phenomenology of lake scum formation,was selected to work at Clear Lake. He was employed jointly by the Lake County Flood Control and Water Conservation District. His mission was to determine the most common blue green algae in the lake and to explore its nutritional requirements, growth characteristics and occurrence in the lake. At the same time, Mr. Mitchell Sabanas, Mechanical Engineer and a Senior Laboratory Mechanician at the University of California was employed to begin a detailed exploration of systems whicy could be utilized for direct algae skimming and removal of algae from the lake. Mr. Henry Gee, Research Chemist in the Sanitary Engineering Research Laboratory at the University, was employed as Project Analyst because of his expertise in analytical methods.

Interim progress of the work has been reported to EPA in a series of six formal progress reports which are listed in the reference section of this report (5 - 10 inclusive). As indicated in these reports, Gaonkar, by October, 1970, had determined that Aphanizomenon was a major year-round algae in the lake and had completed the experimental work on the growth characteristics of Aphanizomenon. This work was prepared as a dissertation which was approved in July 1971(10).

Also, as indicated in the reports, during Dr. Gaonkar's experimental work on the lake, Mr. Sabanas had developed and tested a complete workable algal removal system. However, early rains in the fall of 1970 obliterated the algal scums in the lake and prevented any systematic removal experiments that Fall. It was apparent from preliminary work with the first model that a special pickup unit which moved into the algae was essential. A preliminary model of such a unit based on a moving belt system and called the draper unit was built. However, before testing could be accomplished, the project was out of time and virtually out of funds. Several no-cost extensions of the project were requested because of a lack of floating algae for test purposes. The first prototype draper unit was tested very briefly at the lake in the Fall of 1971 and was found wanting in that algal scums were not taken up well and indeed were actually repelled by the unit. The unit was returned to the University for modifications, which were made during the winter and spring of 1972. With the modifications complete the unit was to be moved to Clear Lake in the Fall of 1972, but the project was again out of funds and time and an illness had overtaken Mr. Sabanas. Consequently, some testing of the modified unit was attempted on an experimental pond in Richmond. It was evident from these tests that the revised draper pickup unit also could not work and a different kind of unit would probably be required.

On December 21, 1972, Mr. Sabanas had a massive heart attack and passed away on December 25, 1972. Following Mr. Sabanas' death, a re-analysis of the pickup problem was made and it was determined that the hydrophilic properties of micro-algae scum made the draper unit basically unfeasible and demanded that a "positive capture" type of unit be employed.

In order to continue the project, the Clear Lake Council at the request of the Research Advisory Board in the Fall of 1972 recommended support for the project from the Clear Lake Board of Supervisors for the continuation of the research at Lake County expense. This was voted in principle by the Board of Supervisors in the Fall of 1973 and funds were appropriated in the Fall of 1974, but are at this time not yet available within the University. These funds, when available, will be used to construct a third generation algae pickup unit, which has been designed on the basis of all past experience and described briefly herein. The purpose of this new unit, like the others, will be to skim and concentrate hydrophilic surface-growing micro-algae in natural bodies of water. Should this unit prove successful, additional state or federal grants may be sought to demonstrate the systematic removal of floating algae from Clear Lake on a larger scale.

CHARACTERISTICS OF CLEAR LAKE

Geography

As described by Lallatin, et al,(11) Clear Lake is located in Lake County, California, about 130 airline kilometers due north of San Francisco. It has a surface area of 17,8000 hectares, a shoreline length of 110 kilometers, a volume of about 1.43 billion cubic meters, a mean depth of about 7.9 meters, and a maximum depth of 18 meters. A map of Clear Lake and its location in California is shown in Figure 1. Clear Lake has three arms called Upper Arm, Oaks Arm and Lower Arm. The size, depth, volumes, and shoreline length of the arms and the entire lake are tabulated in Table 1A.

TABLE 1A

SUMMARY OF SURFACE AREA, VOLUME, AVERAGE DEPTH
AND SHORELINE OF EACH ARM OF CLEAR LAKE(11)

	Upper Arm	Oaks Arm	Lower Arm	Totals
Surface area, Hectares	12,800	1,300	3,700	17,800
Liters x 10^{12}	0.899	0.137	0.383	1.42
Average depth, meters	7.1	11.1	10.3	7.9
Length of shoreline, kilometers	56	19	39	114

Uses of Clear Lake

Because of its proximity, warm waters, and pleasant surroundings, Clear Lake has for decades served as a recreational area for the citizenry of the San Francisco Bay Area. As evidenced by the large amounts of organic matter found in test borings of the bottom muds of the lake, it was apparently undergoing extensive eutrophication long before the first

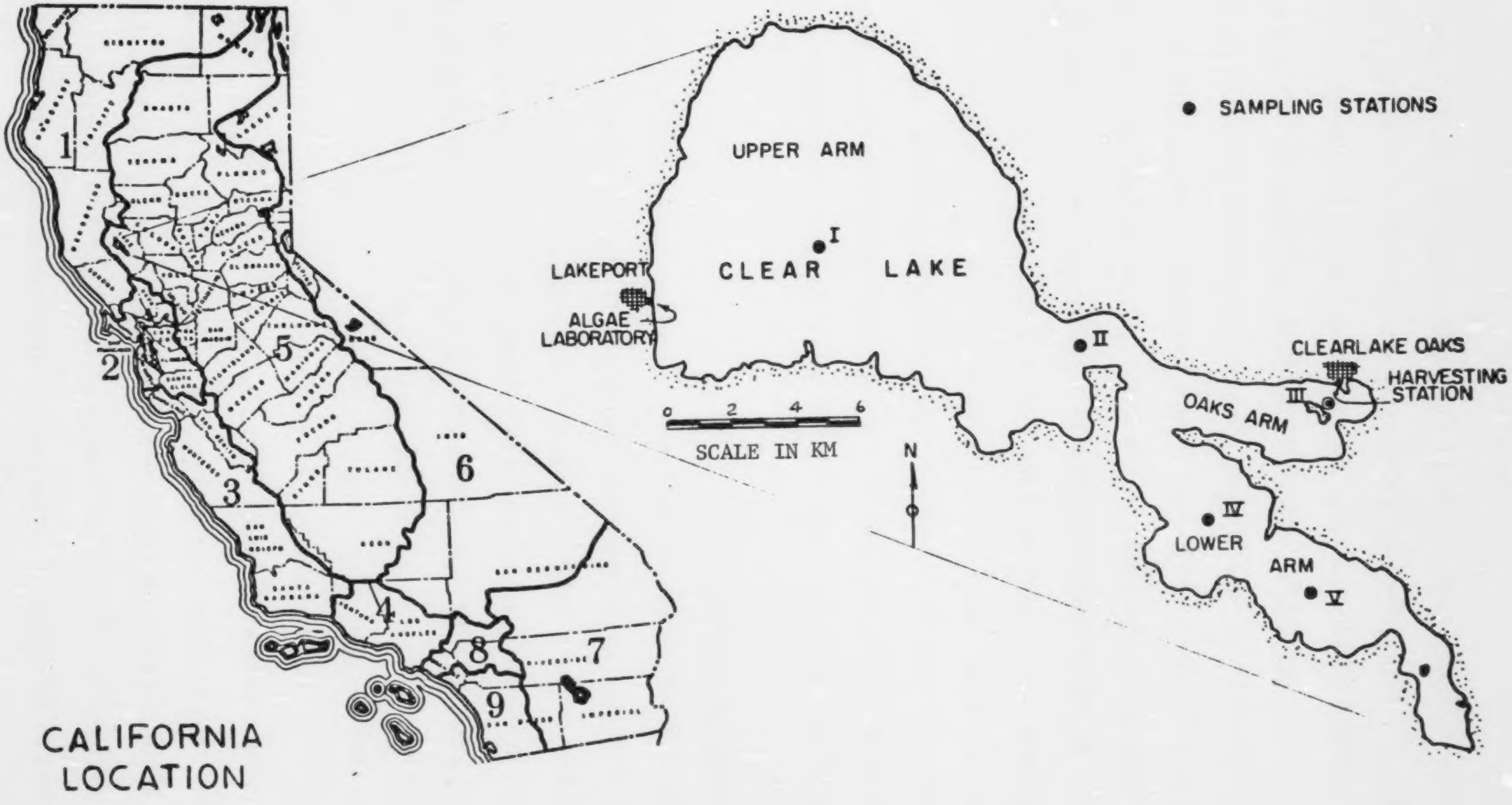

● SAMPLING STATIONS
UPPER ARM
CLEAR LAKE
I
LAKEPORT
ALGAE LABORATORY
II
CLEARLAKE OAKS
HARVESTING STATION
III
OAKS ARM
0 2 4 6
SCALE IN KM
N
IV
LOWER ARM
V
1
2
3
4
5
6
7
8
9
CALIFORNIA LOCATION

FIGURE -1 Map of Clear Lake Showing Arms and Stations

Caucasian settlers came to the area. As described by Lallatin and Clawson,(11) archaeological evidence shows that the lake served as a major source of food and water for an Indian population in the area. With the arrival of settlers, commercial fishing, agriculture, mining, and construction activities began along the lake's shoreline and upon its watershed and have continued to this day. There has been a constant increase in population and in recreational activities. The current resident population of about 22,000 persons increases to a summer population of over 50,000 persons with summer weekend peaks near 100,000 persons. These activities and population increases are believed to have led to an acceleration in the eutrophication of the lake. The lake's utility is now sometimes impaired during the summer and fall due to algal scum formation. However, at many times during the year, little algal material is evident in the water.

Eutrophication Problem

The eutrophication of the lake is sometimes manifested in the formation of floating algae which eventually may form films which in turn may consolidate to form large algal mats. Microscope studies show that the mats of algae which accumulate mainly along the southern and eastern shores of Clear Lake are comprised mainly of the blue-green algae *Aphanizomenon*, *Microcystis*, and *Anabaena*. During the year of Gaonkar's observations, January 1969 to January 1970, *Aphanizomenon* was a predominant species in the lake(10). Its biomass was estimated to be more than 95 percent of the algae in most samples examined. Studies by Horne and Goldman(12)(13) have indicated that *Anabaena* and *Microcystis* tend to predominate during warm summer months while *Aphanizomenon* predominates during the late fall, winter and spring months. During the summer of 1974, the lake developed a substantial bloom of *Melosira*, a diatom, which appeared as small floating particles in the lake's surface waters.

Average Water Quality

Gaonkar(10) has summarized the average water quality characteristics in Clear Lake. This summary is shown in Table 1B.

It is well known that water quality, algal species, climate and lake geometry interact to produce algal scums which in turn effect water quality, but the detailed mechanisms of the interactions are not generally understood. In this section of the report an effort is made to examine in some detail the phenomenology of surface bloom and mat formation with the objective of improving our understanding of a condition which we hope to ameliorate.

TABLE 1B

PHYSICAL AND CHEMICAL CHARACTERISTICS OF CLEAR LAKE WATER (10)

Temperature	5.2-29.0°C
Conductivity	220-330 micromho at 25°C
pH	7.1-9.2
Total Dissolved Solids	138-156 ppm
Total Hardness	103-118 mg/l as $CaCO_3$
Bicarbonate	120-160 mg/l
Nitrate Nitrogen	0.01-0.53 mg/l
Ammonia Nitrogen	0.0-0.27 - 0.61 mg/l
Organic Nitrogen	0.3-0.6 - 1.8 mg/l
Ortho PO_4-P	0.01-0.46 mg/l
Total PO_4-P	0.03-0.55 mg/l
Sulfate	13-30 mg/l
Calcium (Ca)	20-25 mg/l
Magnesium (Mg)	14-18 mg/l
Sodium (Na)	2.4-12.0 mg/l
Potassium (K)	2.2-5.0 mg/l
Iron (total) (Fe)	0.05-0.24 mg/l
Aluminum (Al)	0.033-0.113 mg/l
Boron (B)	0.1-2.2 mg/l
Manganese (Mn)	0.1-1.0 mg/l
Cobalt (Co)	<3.3 μg/ℓ
Copper (Cu)	0.05-0.19 mg/l
Zinc (Zn)	0.02-0.05 mg/l
Molybdenum (Mo)	<0.67 μg/ℓ
Cadmium (Cd)	<3.3 μg/ℓ
Chromium (Cr)	<3.3 μg/ℓ
Vanadium (V)	2.0-3.0 μg/ℓ
Titanium (Ti)	1.3-8.0 μg/ℓ
Nickel (Ni)	1.5-4.8 μg/ℓ

A number of systematic investigations of water quality in Clear Lake, its primary productivity and its pollutional characteristics have been made by Goldman(14), Hom(15), Lallatin(11), and Horne(12)(13). Although each of these quality evaluations will be drawn upon in this report the most pertinent to this discussion are those conducted by the Department of Water Resources, March 1969 to September 1969, and reviewed by Sawyer, Goldman and Oswald(16), and those conducted by Gaonkar from October 29, 1969 to October 15, 1970(10). These will be further reviewed and drawn upon in considerable detail herein.

SECTION III

WATER QUALITY AND ALGAL BLOOMS

DEPARTMENT OF WATER RESOURCES STUDIES

The analytical results of the California State Department of Water Resources (DWR) for Clear Lake 1969 are highly pertinent to this report in that they provide information essential to the development of a phenomenological model of algal scum formation in Clear Lake. The results are reported in three Stations designated as 1, 3 and 4. Positions of the stations are shown in Figure 1 in which Stations 1, 3 and 4 roughly correspond with Stations I, III and IV. The DWR results indicate spatial and temporal variations of certain physical conditions and certain key parameters in the lake and their effects on algae in the system. These data tabulated from March to September 1969 are presented in their entirety in Tables 2, 3 and 4 for Stations 1, 3 and 4 respectively sampled at the lake surface and Tables 5, 6 and 7 for Stations 1, 3 and 4 respectively sampled at the lake bottom. In addition to a tabulation of DWR data, these tables also contain derived information including the percent oxygen saturation based on dissolved oxygen and temperature observations, and a light absorption coefficient α based on the Beer-Lambert Law and computed as follows:

$$\alpha = \frac{9}{Xd} \qquad (1)$$

in which X is the mean dry weight concentration of algal cells in the photic zone (assuming that 1×10^7 cells/ml = 1 mg/l) and d is the secchi disk depth x 2 expressed in cm. The value 9 is an arbitrarily selected constant based on value of $\ln I_o - \ln I_d$ in which ln indicates natural logarithms, I_o is assumed to be the surface light intensity in foot-candles taken at 8,000 and I_d is assumed to be the light intensity of 1 foot-candle

TABLE 2 CLEAR LAKE DWR STATION 1 SURFACE

Date 1969	Surf Temp, °C	Sat DO, mg/L	Surf DO, mg/L	% Sat	Org N, mg/L	NH_3 N, mg/L	NO_3 N, mg/L	Tot N mg/L	Ortho P, mg/L	Tot P, mg/L	Secci d, M	Plank Mean, mg/L	α x 10^{-3}	Plank Mass, mg/cm^2
3/11	8.8	11.6	11.7	101	0.4	0.00	0.35	0.75	0.05	0.13	0.2	0.1	2,250	0.04
4/2	13.0	10.6	10.7	101	0.4	0.00	0.33	0.73	0.05	0.13	0.25	0.06	2,570	0.05
4/17	18.2	9.5	10.4	110	0.3	0.00	0.31	0.61	0.02	0.16	0.45	0.43	3,340	0.02
4/29	18.2	9.5	9.7	102	0.4	0.00	0.34	0.74	0.03	0.12	0.50	0.01	15,000	0.01
5/13	16.7	9.8	9.0	92	0.3	0.00	0.29	0.69	0.06	0.06	0.50	0.015	6,000	0.01
5/27	20.3	9.1	9.0	99	0.3	0.01	0.22	0.53	0.03	0.08	1.20	0.015	2,500	0.01
6/11	21.2	8.9	8.5	95	0.6	0.00	0.05	0.65	0.02	0.17	1.30	1.2	28.7	0.64
6/25	21.7	8.9	8.3	93	0.5	0.00	0.05	0.55	0.02	0.07	0.40	1.5	75.0	0.91
7/2	23.5	8.6	9.5	110	0.4	0.00	0.06	0.46	0.03	0.10	1.5	1.3	23.0	2.0
7/9	23.7	8.6	9.5	110	0.5	0.00	0.04	0.54	0.01	0.10	1.4	1.9	16.8	1.45
7/23	27.8	8.0	10.0	125	0.4	0.00	0.01	0.41	0.00	0.06	3.0	0.35	43.0	0.17
8/6	25.5	8.3	7.2	87	0.5	0.00	0.04	0.54	0.11	0.15	1.55	0.20	145.0	0.09
8/19	24.8	8.4	6.3	75	0.4	0.00	0.01	0.41	0.22	0.23	3.25	0.30	46.0	0.10
9/2	25.0	8.4	7.2	86	0.4	0.00	0.00	0.40	0.22	0.22	3.3	0.25	54.0	0.11
9/17	23.3	8.6	6.0	70	0.5	0.00	0.01	0.51	0.32	0.37	1.2	0.08	470	0.05
9/30	22.0	8.8	7.5	85	0.4	0.00	0.04	0.44	0.19	0.22	0.9	0.01	5,000	0.01
AVERAGES					0.42	0.00	0.135	0.55	0.08	0.15				

TABLE 3 CLEAR LAKE DWR STATION 3 SURFACE

Date 1969	Surf Temp, °C	Sat DO	Surf DO	% Sat	Org N	NH_3 N	NO_3 N	Tot N	Ortho P	Tot P	Secci d, M	Plank Mean, mg/L	α x 10^{-3}	Plank Mass, mg/cm^2
3.11	8.7	11.7	11.5	98	0.4	0.00	0.50	0.90	0.06	0.20	0.4	0.2	550	.055
4.2	14.2	10.3	10.7	104	0.4	0.00	0.46	0.86	0.04	0.09	0.5	0.1	900	.081
4.17	16.6	9.8	10.3	105	0.4	0.00	0.40	0.80	0.03	0.10	0.6	0.2	390	.100
4.29	20.0	9.2	10.8	117	0.8	0.00	0.33	1.13	0.03	0.19	0.9	1.8	28	.670
5.13	23.0	8.7	13.1	150	1.7	0.00	0.02	1.72	0.00	0.09	0.6	9.0	8.3	2.0
5.27	21.3	9.0	9.3	103	0.4	0.05	0.02	0.47	0.01	0.19	1.9	0.9	23.7	1.0
6.11	21.7	8.9	8.7	98	0.9	0.06	0.03	0.99	0.03	0.27	0.9	4.8	10.5	1.6
6.25	22.0	8.8	7.7	87	0.6	0.05	0.04	0.69	0.02	0.11	0.4	0.9	125	1.0
7.3	22.7	8.7	11.4	131	1.3	0.00	0.03	1.33	0.01	0.12	0.9	5.3	9.4	3.8
7.9	25.5	8.3	7.9	95	0.6	0.27	0.00	0.87	0.04	0.07	2.0	0.7	32	.37
7.23	29.0	7.7	13.8	179	0.8	0.00	0.02	0.82	0.00	0.05	2.3	2.8	7.0	1.32
8.4	26.0	8.3	8.7	105	0.4	0.01	0.03	0.44	0.02	0.08	1.2	2.3	16.3	1.76
8.6	26.6	8.2	11.1	135	0.8	0.00	0.03	0.83	0.02	0.08	1.1	1.6	25.4	0.99
8.19	26.0	8.3	11.0	137	1.8	0.00	0.01	1.81	0.08	0.25	0.6	5.5	13.5	2.47
9.2	26.0	8.3	11.3	136	0.8	0.00	0.00	0.80	0.10	0.12	1.8	2.0	12.5	1.10
9.17	23.4	8.6	8.8	102	1.1	0.00	0.01	1.11	0.02	0.14	0.9	2.3	21.6	0.72
9.30	23.0	8.7	11.3	130	1.4	0.06	0.03	1.49	0.05	0.09	1.8	5.4	9.2	1.25
AVERAGES →					0.86	0.03	0.115	1.00	0.033	0.13				

TABLE 4 CLEAR LAKE DWR STATION 4 SURFACE

Date 1969	Surf Temp, ^oC	Sat DO, mg/L	Surf DO, mg/L	% Sat	Org N, mg/L	NH_3 N, mg/L	NO_3 N, mg/L	Tot P, mg/L	Ortho P, mg/L	Tot P, mg/L	Secci d, M	Plank Mean, mg/L	α $\times 10^{-3}$	Plank Mass mg/cm^2
3.11	8.4	11.8	11.5	98	0.4	0.00	0.43	0.83	0.06	0.60	0.2	0.02	2,250	.026
4.2	13.0	10.6	10.0	95	0.3	0.03	0.40	0.73	0.06	0.13	0.3	0.03	5,000	.049
4.17	16.2	9.9	10.1	102	0.4	0.00	0.42	0.82	0.04	0.12	0.5	0.015	6,000	.018
4.29	18.3	9.5	9.5	100	0.4	0.00	0.41	0.81	0.04	0.09	0.4	0.01	1,130	.048
5.13	22.0	8.8	10.0	113	0.4	0.00	0.23	0.63	0.02	0.03	0.75	0.04	150	.54
5.27	21.0	9.0	8.7	97	0.4	0.02	0.15	0.57	0.03	0.06	1.5	0.3	90	.33
6.11	23.3	8.6	8.4	98	0.7	0.02	0.06	0.78	0.03	0.10	0.90	1.5	33.3	1.28
6.25	21.8	8.9	8.0	90	0.5	0.04	0.06	0.60	0.04	0.13	1.0	1.2	37.4	1.13
7.3	21.8	8.9	8.6	97	0.8	0.07	0.07	0.94	0.06	0.11	1.3	1.8	19.2	0.77
7.9	27.5	8.0	19.5	244	1.9	0.06	0.04	2.00	0.02	0.13	0.2	10.8	21.4	3.56
7.23	28.1	7.9	10.6	151	0.5	0.00	0.00	0.50	0.01	0.04	2.5	0.6	30.0	0.75
8.6	24.3	8.5	6.6	78	0.6	0.05	0.04	0.69	0.09	0.17	1.25	5.0	7.2	2.50
8.19	26.0	8.3	8.8	106	0.6	0.00	0.02	0.62	0.11	0.17	2.4	2.8	6.7	2.72
9.2	25.1	8.4	11.1	132	1.1	0.05	0.00	1.15	0.14	0.22	1.3	2.5	13.8	1.05
9.17	23.6	8.6	7.2	84	0.8	0.00	0.02	0.82	0.14	0.21	0.7	1.0	64.0	0.34
9.30	22.2	8.8	7.3	83	0.5	0.02	0.06	0.58	0.13	0.18	0.5	0.7	128	0.28
AVERAGES →					0.65	.023	0.15	0.85	0.06	0.15				

TABLE 5 CLEAR LAKE DWR STATION 1 BOTTOM

Date 1969	Approx Depth, M	Bott Temp	Sat DO	Bott DO	% Sat	Org N mg/L	NH_3 N mg/L	NO_3 N mg/L	Tot N mg/L	Ortho P mg/L	Tot P mg/L	Plankton Approx., mg/L
3.11	8	8.0	11.8	11.6	98	0.3	0.00	0.34	.64	0.05	0.19	0.00
4.2	7.4	11.3	11.1	7.8	70	0.3	0.00	0.36	.66	0.05	0.10	0.02
4.17	8.0	15.0	10.1	9.6	95	0.3	0.00	0.33	.63	0.05	0.18	0.03
4.29	8.0	15.6	10.0	6.2	62	0.4	0.00	0.36	.76	0.05	0.31	0.01
5.13	8.5	14.5	10.3	7.3	71	0.3	0.00	0.34	.64	0.06	0.07	0.01
5.27	7.5	16.5	9.8	5.1	52	0.2	0.05	0.25	.50	0.05	0.15	0.01
6.11	8.0	20.5	9.1	7.2	79	0.3	0.06	0.04	.40	0.02	0.07	0.20
6.25	6.5	21.3	8.9	8.3	93	0.4	0.00	0.04	.44	0.02	0.09	0.60
7.2	6.5	20.2	9.1	7.6	84	0.4	0.02	0.11	.53	0.04	0.12	0.80
7.9	7.0	21.5	8.9	3.4	38	0.4	0.00	0.09	.49	0.04	0.08	0.00
7.23	7.0	23.5	8.6	0.2	2.3	0.5	0.14	0.03	.67	0.16	0.16	0.06
8.6	7.0	23.2	8.6	0.0	0.0	0.4	0.13	0.03	.56	0.31	0.55	0.00
8.19	7.0	24.5	8.5	5.6	66	0.4	0.01	0.02	.43	0.23	0.25	0.05
9.2	6.5	24.0	8.5	3.4	40	0.4	0.00	0.00	.40	0.24	0.24	0.03
9.17	6.5	22.8	8.7	4.5	52	0.6	0.00	0.02	.62	0.32	0.34	0.10
9.30	6.0	21.2	9.0	4.3	48	0.4	0.01	0.06	.47	0.20	0.23	0.01

TABLE 6 CLEAR LAKE DWR STATION 3 BOTTOM

Date 1969	Approx Depth, M	Bott Temp, °C	Sat DO, mg/L	Bott DO, mg/L	% Sat	Org N, mg/L	NH_3 N, mg/L	NO_3 N, mg/L	Tot N, mg/L	Ortho P, mg/L	Tot P, mg/L	Plank Approx, mg/L
3.11	11	8	11.8	11.0	93	0.4	0.00	0.50	0.90	0.05	0.18	0.01
4.2	12	12.0	10.8	6.8	53	0.5	0.02	0.46	0.98	0.04	0.08	0.02
4.17	11	13.5	10.5	9.5	90	0.4	0.01	0.41	0.82	0.04	0.17	0.02
4.29	11	16.5	9.8	8.9	91	0.4	0.00	0.39	0.79	0.04	0.12	0.01
5.13	11	18.0	9.5	4.3	45	0.3	0.01	0.33	0.64	0.04	0.06	0.01
5.27	11	19.0	9.3	8.9	95	0.5	0.06	0.04	0.60	0.01	0.04	0.50
6.11	11	21.0	9.0	5.3	59	0.6	0.20	0.03	0.83	0.04	0.20	0.05
6.25	11	22.0	8.8	7.5	85	0.7	0.06	0.04	0.81	0.03	0.15	1.10
7.3	11	21.0	9.0	7.0	78	0.8	0.02	0.04	0.86	0.02	0.08	0.40
7.9	10	21.5	8.9	0.8	09	0.5	0.45	0.04	0.99	0.14	0.14	0.01
7.23	10	23.0	8.7	0.0	0.0	0.6	0.76	0.02	1.38	0.36	0.42	0.01
8.4	10	25.0	8.4	0.4	05	0.6	0.71	0.04	1.35	0.11	0.27	1.00
8.5	10	25.0	8.4	3.4	40	0.2	0.25	0.03	0.48	0.07	0.11	0.20
8.6	10	24.8	8.4	1.3	15	0.6	0.25	0.04	0.89	0.06	0.12	0.30
8.19	10	24.0	8.5	0.0	0.0	0.6	0.48	0.01	1.09	0.21	0.29	0.00
9.2	10	24.0	8.5	0.0	0.0	0.5	0.13	0.00	0.63	0.12	0.17	0.02
9.17	10	23.0	8.7	6.2	71.0	0.6	0.03	0.02	0.65	0.06	0.12	0.00
9.30	10	22.0	8.8	6.5	74.0	0.5	0.09	0.04	0.63	0.05	0.10	0.02

TABLE 7 CLEAR LAKE DWR STATION 4 BOTTOM

Date 1969	Approx Depth, M	Bott Temp, C	Sat DO, mg/L	Bott DO, mg/L	% Sat	Org N, mg/L	NH_3 N, mg/L	NO_3 N, mg/L	Tot N, mg/L	Ortho P, mg/L	Tot P, mg/L
3.11	13.1	7.5	12.0	11.3	94	0.4	0.00	0.43	0.83	0.05	0.60
4.2	13.0	11.5	11.0	9.8	89	0.3	0.00	0.42	0.72	0.06	0.11
4.17	12.1	13.5	10.5	9.6	91	0.4	0.00	0.42	0.82	0.05	0.09
4.29	13.1	15.5	10.0	9.0	90	0.4	0.00	0.41	0.81	0.04	0.11
5.13	13.1	16.0	9.9	5.7	58	0.4	0.02	0.38	0.80	0.03	0.07
5.27	13.6	18.0	9.5	4.0	42	0.5	0.03	0.20	0.73	0.03	0.14
6.11	13.1	21.0	9.0	7.4	82	0.5	0.11	0.06	0.67	0.05	0.19
6.25	13.0	20.5	9.1	7.6	84	0.5	0.06	0.07	0.63	0.05	0.12
7.3	13.0	20.2	9.1	6.8	75	0.4	0.20	0.07	0.67	0.07	0.16
7.9	12.0	21.1	9.0	4.0	45	0.4	0.14	0.12	0.66	0.08	0.12
7.23	12.0	22.5	8.8	0.0	0	0.4	0.50	0.01	0.91	0.46	0.46
8.6	12.0	24.0	8.5	2.4	28	0.6	0.10	0.04	0.74	0.10	0.16
8.19	12.0	24.5	8.5	6.6	78	0.5	0.06	0.02	0.58	0.12	0.16
9.2	12.0	24.0	8.5	2.2	26	0.6	0.27	0.01	0.88	0.21	0.23
9.17	12.0	22.7	8.8	5.6	63	0.6	0.00	0.02	0.62	0.16	0.23
9.30	11.1	21.0	9.0	6.3	70	0.4	0.01	0.11	0.52	0.14	0.18

at some depth d. Computed values of α are useful because they help to indicate the types of turbidity involved. Values of α for pure cultures of algae are usually from 1×10^{-3} to 3×10^{-3}. Values of α from 5-50 are observed in mixtures of algae and algal cell detritus plus some silt or colloidal precipitates. Values 100 to 1,000 are associated mainly with clay turbidity with some algae, while values of 1,000 to 10,000 are attributable to very muddy silt filled waters with negligible quantities of algae. The plankton mass in the last column is the estimated quantity of pure living algae in a column of lake water 1 cm^2 in area and extending the depth of the lake which would give the light absorption results observed. This number is of use in estimating the increase in photosynthetic biomass, photosynthetic efficiency, and nutrient uptake.

Nitrogen

From the tabulated data, it is evident that during March 1969 organic nitrogen was uniformly distributed throughout the lake, top to bottom, and horizontally at a concentration of about 0.4 mg/l, and that total nitrogen was about twice as much. Inasmuch as there were relatively few algae in the lake at that time, it seems likely that such organic nitrogen was in a soluble or colloidal and perhaps relatively stable (i.e. biologically inert) form. There was apparently little significant variation in organic nitrogen in the upper arm of the lake except for a 0.1 mg/l decline in May and a 0.25 mg/l increase during June. The Oaks Arm evidenced a very slight decrease in organic nitrogen followed by a steady increase from 0.37 to 1.06 mg/l during April, May, June and July. During August there was a decrease in organic nitrogen to 0.60 mg/l followed by an increase to 0.80 mg/l. Lower Lake increased its organic nitrogen to an early peak of 1.05 mg/l in May followed by an abrupt decline in June and a steady increase to

1.10 mg/l during the summer. Organic nitrogen in bottom samples increased very slightly throughout the summer at all stations.

Ammonium nitrogen was quite low in surface waters of the Upper Lake throughout the 1969 period of observation. It tended to increase in the Oaks Arm to a peak of 0.27 mg/l in July after which it declined.

Bottom ammonium for all stations and dates is plotted in Figure 2 as a function of dissolved oxygen. It is evident from the figure that periods of decreased oxygen levels gave rise to ammonium production primarily in Lower Lake, to a lesser extent in the Oaks Arm, and to a very limited extent in Upper Lake. The data in Tables 5, 6 and 7 are indicative that ammonium release was greatest during periods of benthal anoxia when wind mixing was limited and thermal stratification occurred due to the presence of a dense algal bloom. In the case of Upper Lake, it is so shallow and hence subject to relatively deep wind mixing that complete benthal anoxia rarely occurred. Moreover, during 1969, the inorganic turbidity in Upper Lake was so intense that algal growth was limited and strong thermal gradients did not occur. Stations 3 and 4 had less turbidity and as a result developed relatively intense algal blooms accompanied by marked thermal stratification and periods of intense ammonium emission form the bottom. The fact that ammonium emission reached its peak in all limbs in July and then declined is an indication that the decomposing material was comprised mainly of organic deposits from the preceding fall or winter rather than from decomposition of newly deposited material. This follows because newly deposited material was sparse in July, the main algal bloom and settling or skimming occurring later in the summer.

There is little question that released ammonium becomes blended into the overlying waters by some transport mechanism such as wind mixing but,

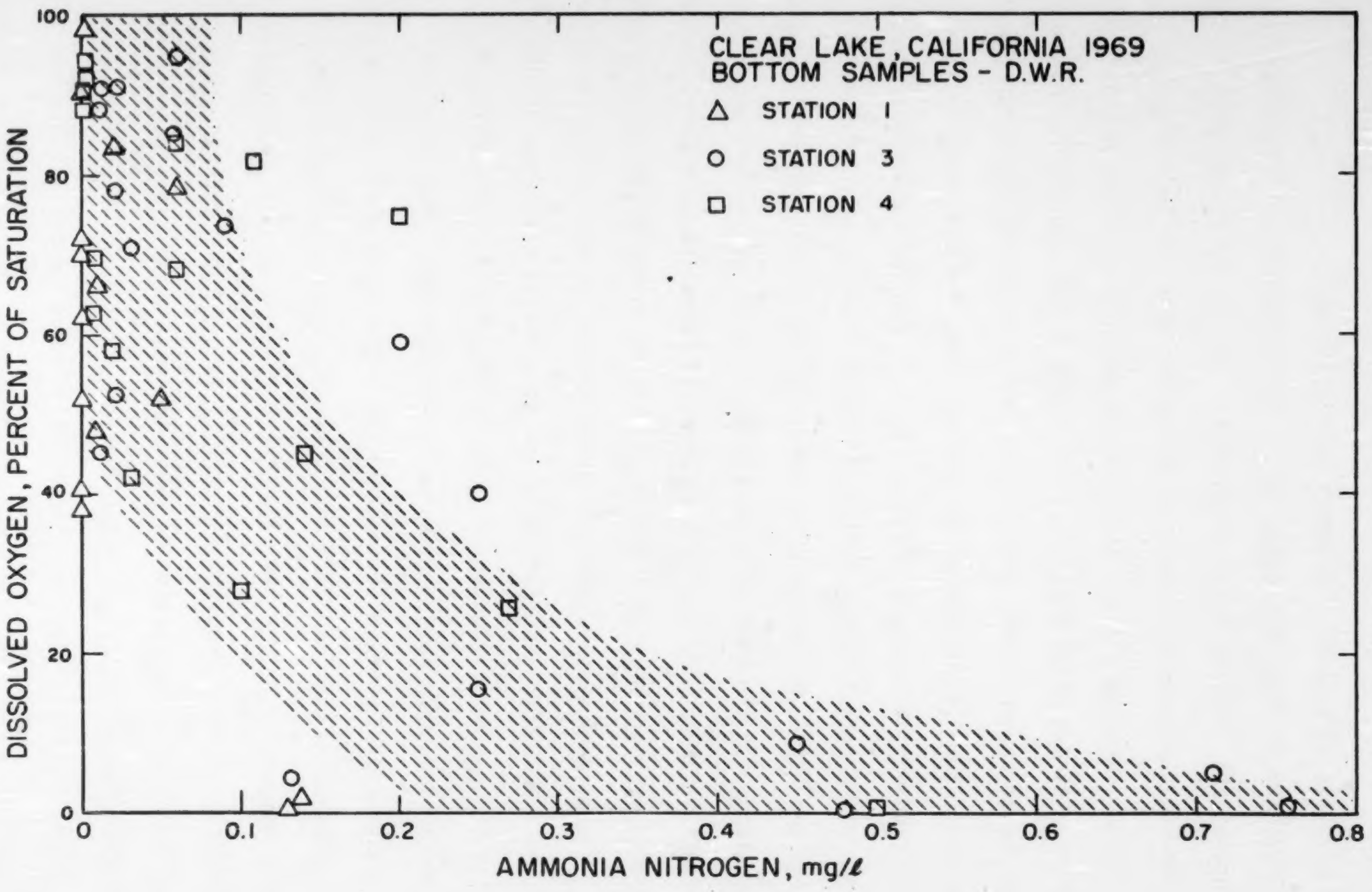


FIGURE 2 Relationship between dissolved oxygen and ammonia nitrogen in bottom waters of Clear Lake

there being little ammonium in the surface samples, some mechanism for ammonium loss is also required. Some ammonium is doubtlessly lost to the atmosphere during wave action and some of the ammonium is oxidized to nitrate or reduced to cellular material by microbial assimilation. There is strong evidence of algal uptake of ammonium in Lower Lake (Station 4) because at that station, ammonium depletion always accompanied large algal blooms. This was also the case in the Oaks Arm, but in Upper Lake there was little ammonium found in surface water in spite of the fact that ammonium release was evidenced in the bottom samples. The disappearance of the released ammonium in the Upper Lake was apparently due to the conversion of ammonium to nitrate by nitrifying bacteria. At least ammonium loss was more rapid than predicted ammonium uptake by the algae. Inhibited algal growth was probably caused by the high turbidity in the Upper Lake samples which absorb light and limit suspended algal growth. This permitted time for a nitrate forming microbial population to become established in the system.

Nitrate differed in each arm of the lake in March, the lowest values 0.35 mg/l in Upper Lake, the larger values 0.43 mg/l in Lower Lake, and intermediate values (0.40 mg/l) in the Oaks Arm. As the lake warmed, nitrate was apparently removed from the lake water by two mechanisms--algal growth and denitrification. A rapid decrease in nitrate nitrogen occurred in the lake from May 27 to June 11 as the water temperature changed from 16.5°C to 20.5°C. As an example at Station 1 bottom there was a decrease in nitrate nitrogen from 0.36 mg/l April 29 to 0.04 mg/l on May 7, a change of 0.32 mg/l. If all of this nitrate has been taken up by 8% nitrogen algae, the concentration of algae should have increased during that time from nil to 4 mg/l. On the contrary, according to a phytoplankton survey, the concentration of algae at Station 1 only increased during May from about .025 mg/l to about .05 mg/l--a factor of almost 100 below that which would be expected on the basis of nitrate depletion. The spring bloom of algae amounting to less than 1 mg/l dry weight appears thus to have occurred after nitrate reached a low level. A mechanism other than algal uptake is therefore required to account for the sudden nitrate depletion that occured in May in Station 1. This mechanism as noted above is probably denitrification, the bacterial conversion of nitrate to molecular nitrogen. Such denitrification is known to occur in sewage ponds and should also occur readily in the rich organic interphase between overlying water and the anaerobic bottom deposits known to exist in Clear Lake. This process evidently occurs in many natural systems when there is soluble organic matter, an absence of molecular oxygen and a temperature above about 12°C. Gaonkar(10)(see Table 20) found the bottom of Clear Lake to be 15% organic. While dissolved oxygen was found to be present near the bottom in Clear Lake during May, a decrease in dissolved oxygen occurred near the bottom in the May 27 sample and doubtlessly, dissolved oxygen reached zero frequently within the layer of sediment. Hence, the conditions required for denitrification were met.

To indicate which factor--anoxia or temperature--most strongly influenced nitrate loss in Clear Lake, plots were made of the 1969 DWR data for nitrate versus dissolved oxygen and nitrate versus temperature in bottom samples. These plots are shown in Figures 3 and 4. It seems evident from the plots that although an absence of dissolved oxygen was associated with the nitrate decrease (Figure 3), the major influence on nitrate decrease occurred during temperature changes. According to Figure 4, nitrate concentration was inversely proportional to temperature and the decrease in nitrate between 12°C and 22°C was linear. This

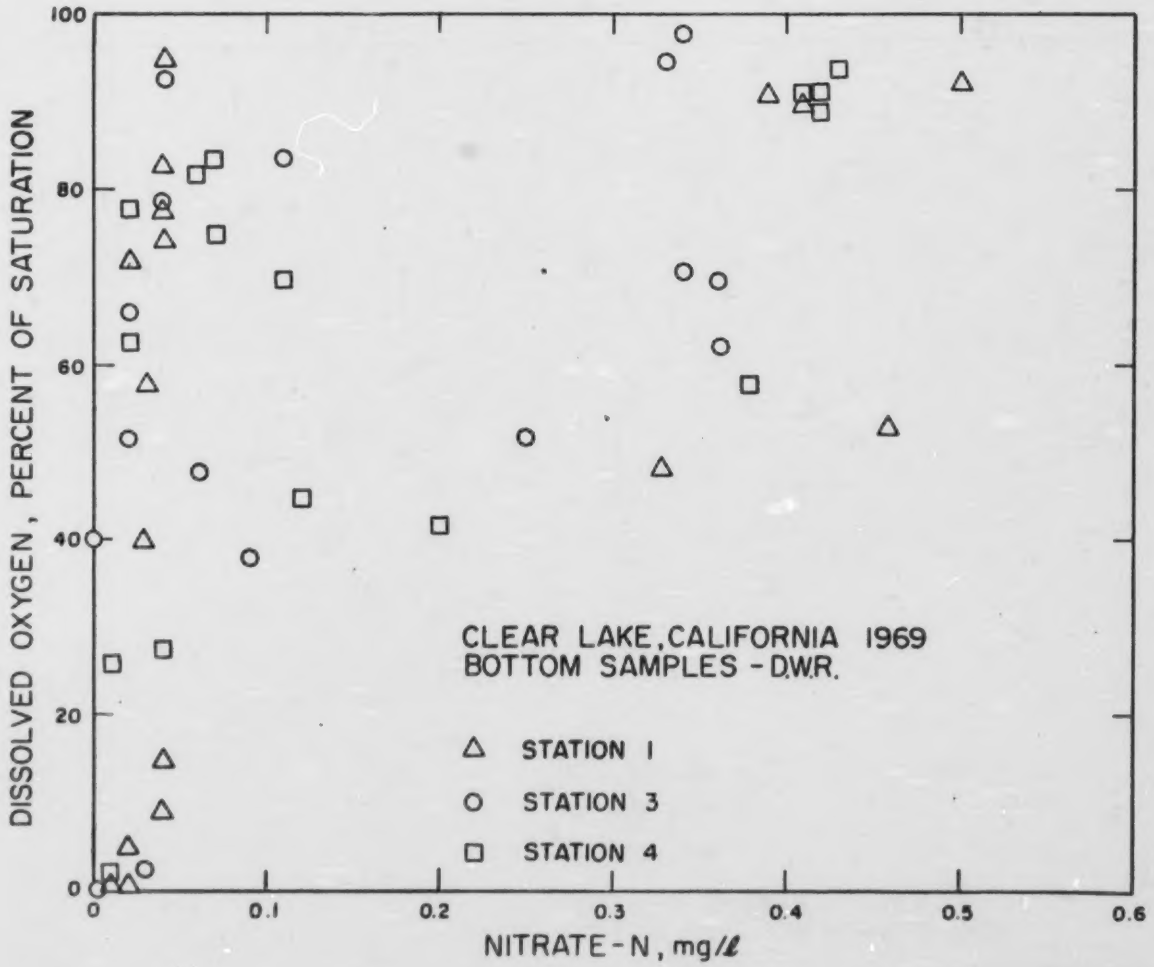


FIGURE 3 —Relationship between nitrate Nitrogen and dissolved oxygen in Clear Lake bottom waters

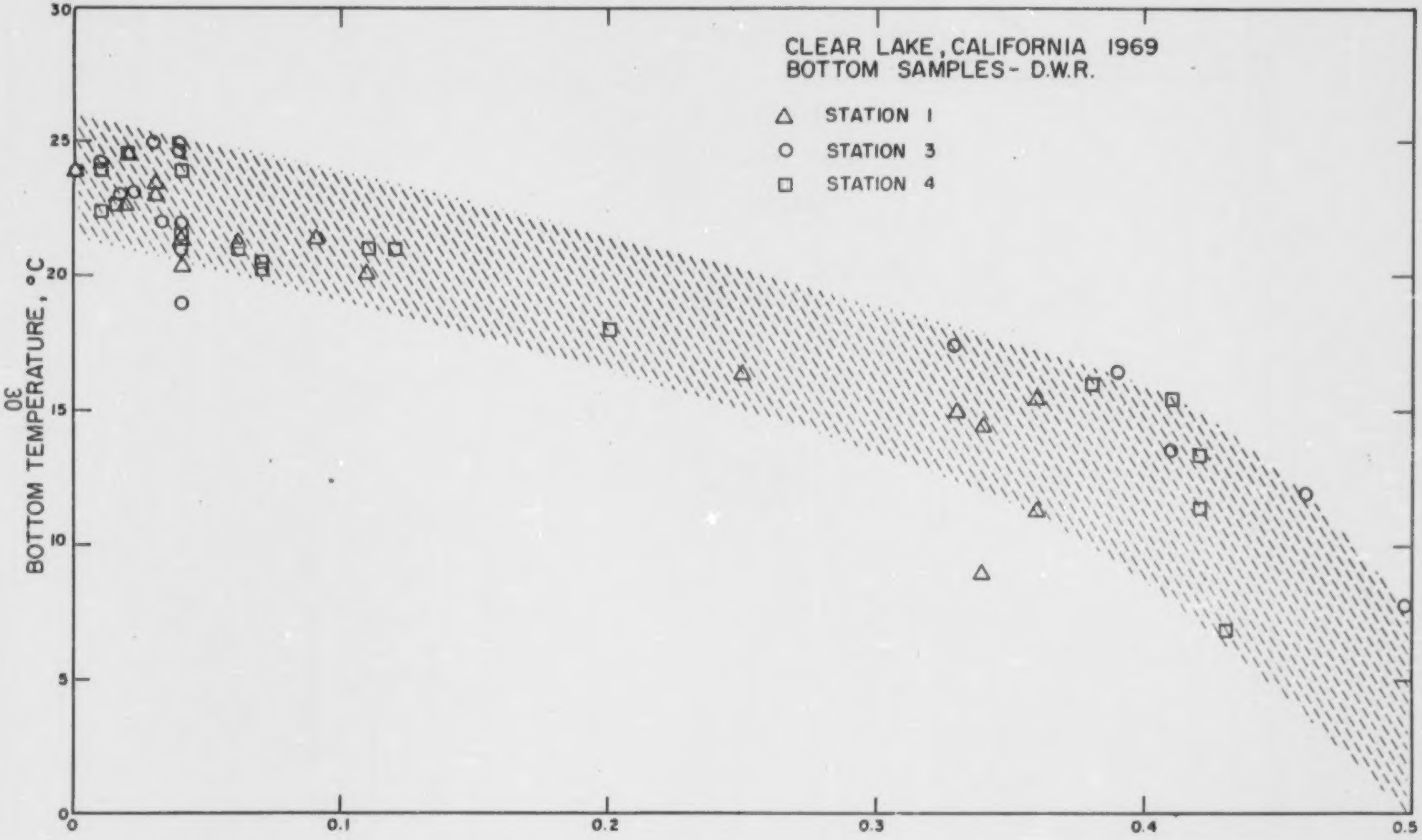


FIGURE 4 Relationship between nitrate and temperature in bottom waters of Clear Lake

evidence strongly suggests that bacterial denitrification was, in this case, more active than algal growth as a major factor in the decrease in nitrate concentration in the lake water. It is interesting to note that the shaded area in Figure 4 closely follows the denitrification curve developed by DWR in their studies of denitrification of drainage waters at Firebaugh, California (18). As noted previously, depletion of bottom samples,if taken up by algae, would have produced 4.5 mg/l of algae, whereas the actual algal concentration in the entire column was less than 1 mg/l. Moreover, algal uptake of nitrate should not have occurred in the bottom horizon anyway for lack of light. In Station 4, bottom samples of nitrate during May and early June dropped from 0.41 mg/l to 0.03 mg/l, a change of 0.38 mg/l. This is equivalent to 4.6 mg/l of 8% nitrogen algae; whereas the concentration of algae which grew was less than 2 mg/l. Thus, at each bottom station, the rate and amount of algae which grew was not sufficient to account for the rate of decline or total decline in nitrate nitrogen. On the other hand, in the photic zone (surface data), depletion of nitrate accompanied spurts of algal growth (see Table 4, Station 3 surface) April 29 to May 13.

A summary of monthly average organic nitrogen, ammonium nitrogen, nitrate nitrogen and the sum of these three is presented in Table 8, together with monthly average orthophosphate, total phosphate and algae.

With respect to total nitrogen, monthly average values for the three arms of the lake are plotted in Figure 5. It is evident from this figure that during the reported period of observation, the three arms of the lake were behaving essentially independently of one another. The surface waters of Upper Lake lost nitrogen steadily throughout the year; the total loss amounting to 0.3 mg/l or about 300 metric tons. This

TABLE 8 CLEAR LAKE SURFACE NUTRIENTS

Station	Organic N, mg/L			Ammonia N, mg/L			Nitrate N, mg/L			Total N, mg/L			Ortho P, mg/L			Total P, mg/L			Algae[a], mg/L		
Month	1	4	3	1	4	3	1	4	3	1	4	3	1	4	3	1	4	3	1	4	3
March	0.4	0.4	0.40	0.00	0.00	0.00	0.35	0.43	0.50	0.75	0.83	0.90	.05	.060	.06	.13	.60	.20	0.1	0.02	0.2
April	0.37	0.37	0.53	0.00	0.01	0.00	0.33	0.41	0.40	0.69	0.78	0.93	.033	.047	.033	.14	.11	.13	0.03	0.02	0.7
May	0.30	0.40	1.05	0.00	0.01	0.02	0.25	0.19	0.02	0.61	0.61	1.09	.045	.025	.003	.07	.05	.14	0.02	0.04	5.0
June	0.55	0.60	0.75	0.00	0.03	0.06	0.05	0.06	0.04	0.60	0.69	0.84	.020	.035	.025	.12	.12	.19	1.35	1.3	2.9
July	0.43	1.06	0.90	0.00	0.04	0.99	0.04	0.04	0.02	0.47	1.15	1.01	.013	.030	.016	.09	.09	.08	1.20	4.4	2.9
Aug	0.45	0.60	1.00	0.00	0.03	0.00	0.03	0.03	0.02	0.47	0.65	1.03	.180	.110	.040	.24	.17	.14	0.25	3.4	3.1
Sept	0.43	0.80	1.10	0.00	0.02	0.03	0.02	0.03	0.01	0.45	0.85	1.13	.250	.137	.063	.27	.21	.12	0.11	1.7	3.2

[a] Mean Value in Photic Zone

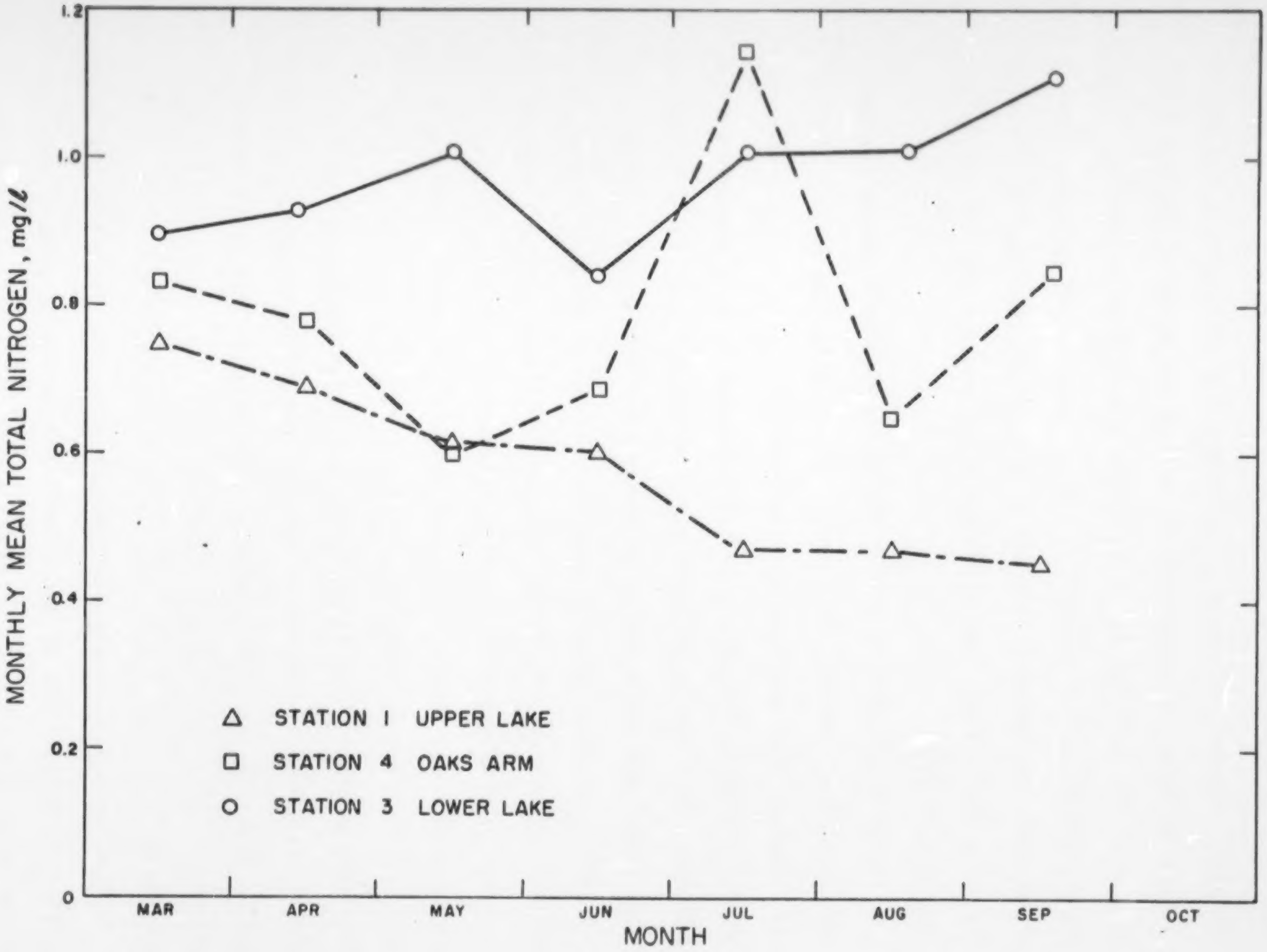


FIGURE 5 Monthly mean total nitrogen in surface waters of Clear Lake

loss could be attributed to sedimentation had there been a loss in organic nitrogen. However, reference Table 8 shows that in Upper Lake organic nitrogen actually increased slightly through the period of observation. In view of the fact that there was little algal growth in the Upper Lake, and consequently, little opportunity for nitrogen fixation and in view of the fact that the major loss was in the nitrate fraction, it is further indicated that nitrate loss in the upper arm of Clear Lake was mainly due to denitrification.

Figure 5 also shows a similar decline in total nitrogen in the Oaks Arm during April and May, the quantity amounting to some 30 tons of nitrogen. However, this was apparently followed by a period of rapid nitrogen increase (probably fixation) and denitrification so that between April and September, there was no net increment in nitrogen. Lower Lake, on the other hand, showed only one period of denitrification followed by a steady increase in nitrogen for a net gain of 0.23 mg/l or about 35 tons of nitrogen in that arm of the lake. The overall loss of nitrogen from the lake due to an excess of denitrification over nitrogen fixation appears to have been 260 tons from March through September, primarily attributable to a lack of nitrogen-fixing algal growth in the upper arm of the lake. This lack of algal growth could initially be accounted for by high and recurrent turbidity in that arm of the lake, but during the summer, some factor other than turbidity inhibited algal growth. This will be discussed below.

Phosphorus

Data for orthophosphate and total phosphate for each arm of the lake, surface and bottom, and for the period March through September, 1969, are presented in Tables 2 to 7 inclusive. A summary for the epilimnion in

Upper Lake, Lower Lake and the Oaks Arm is presented in Table 8. It is evident from an overview of the data that a substantial increase in orthophosphate occurred in August and September, particularly at Station 1, and that a smaller increase occurred at the same time in Station 3 and Station 4. These increases apparently occurred during periods when the dissolved oxygen at the bottom of the lake reached or approached zero. The relationship between bottom dissolved oxygen and bottom orthophosphate release is shown in Figure 6.

The figure indicates that in general, orthophosphate increased as dissolved oxygen in the bottom water decreased. This tends to confirm the hypothesis that intermittent anaerobic conditions preclude methane production and lead to the production and accumulation of organic acids which in turn cause phosphate release.

The anomalously high orthophosphate values at high dissolved oxygen levels in Figure 6 for Station 1 and Station 4 do not refute this relationship. They are attributed to two things. First, the upper arm of the lake is often thoroughly mixed and, hence, phosphate which is released into the bottom waters tends to adhere to silt and is frequently blended into the overlying waters. Also, the Oaks Arm, although slightly deeper than the Lower Lake, is situated at the end of the longest fetch of the lake with respect to prevailing westerly winds so that it receives a more vigorous wind driven wave and current action than does Lower Lake. Secondly, the Upper Lake Station 1 and Station 4 contain more inorganic silt and detritus; hence, it is difficult to obtain representative samples from the bottom. Thus, positive dissolved oxygen values may have come from strata sufficiently above the bottom as to give anomalous readings.

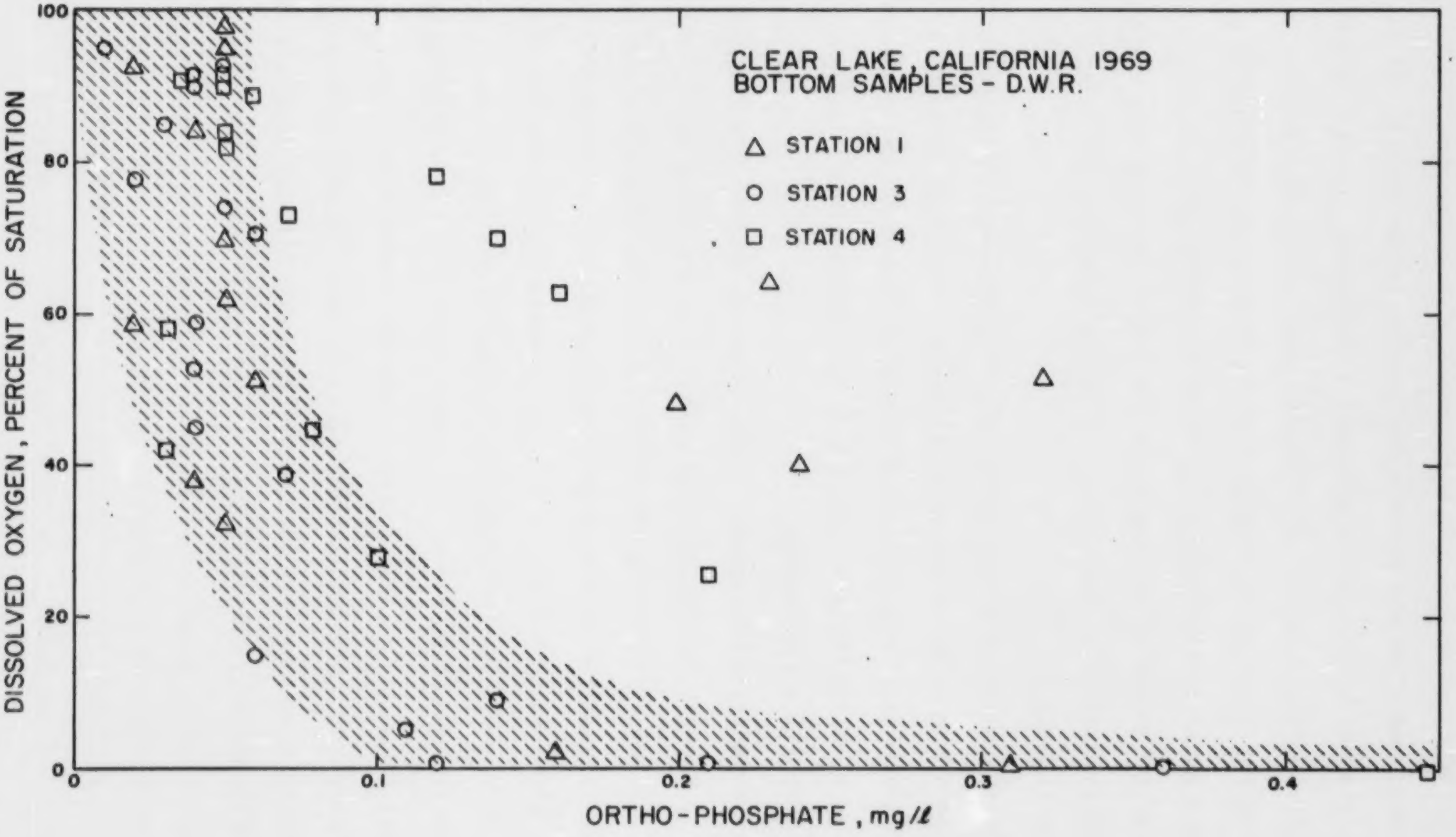


FIGURE 6 Relationship between bottom dissolved oxygen and ortho-phosphate in Clear Lake

To examine the structure of phosphate changes due to algal growth, values for orthophosphate and algal growth are plotted as a function of time for the surface water of each arm of the lake. These plots are shown in Figures 7, 8 and 9.

Figure 7 shows the relationship between algal growth and orthophosphate for Station 1 in the Upper Lake. The results show that a weak (1.9 mg/l) algal bloom occurred during June and July and was terminated when the orthophophate level approached zero. An enormous release of orthophosphate from the bottom layer of Upper Lake ensued during August and September, but apparently did not trigger another algal bloom. One explanation of this anomaly is that possibly some element in addition to phosphorus was either depleted by the prior algal bloom or that some substance was released from the lake mud by the same mechanism which caused the phosphate release. In the latter case, the material released could have been toxic to algae. Horne and Goldman have shown that the addition of small amounts of copper can slow or stop nitrogen fixation in Clear Lake(17).

On the basis of the direct evidence in Figure 7, it seems likely that the phosphate release itself was induced by the mass algal bloom, perhaps by an increase in methane fermentation due to sedimentation of the algal mass leading to vigorous gas production within the bottom deposits. The rising methane bubbles would, of course, have mixed any soluble phosphate present in the mud and any settled algae into waters above the mud and thence into the waters of the surface of the lake. While a similar phenomenon would be expected in the deeper limbs of the lake, there is much less phosphate-bearing silt in the Oaks and Lower Arm, because most of it has settled out by the time water reaches the narrows. There being

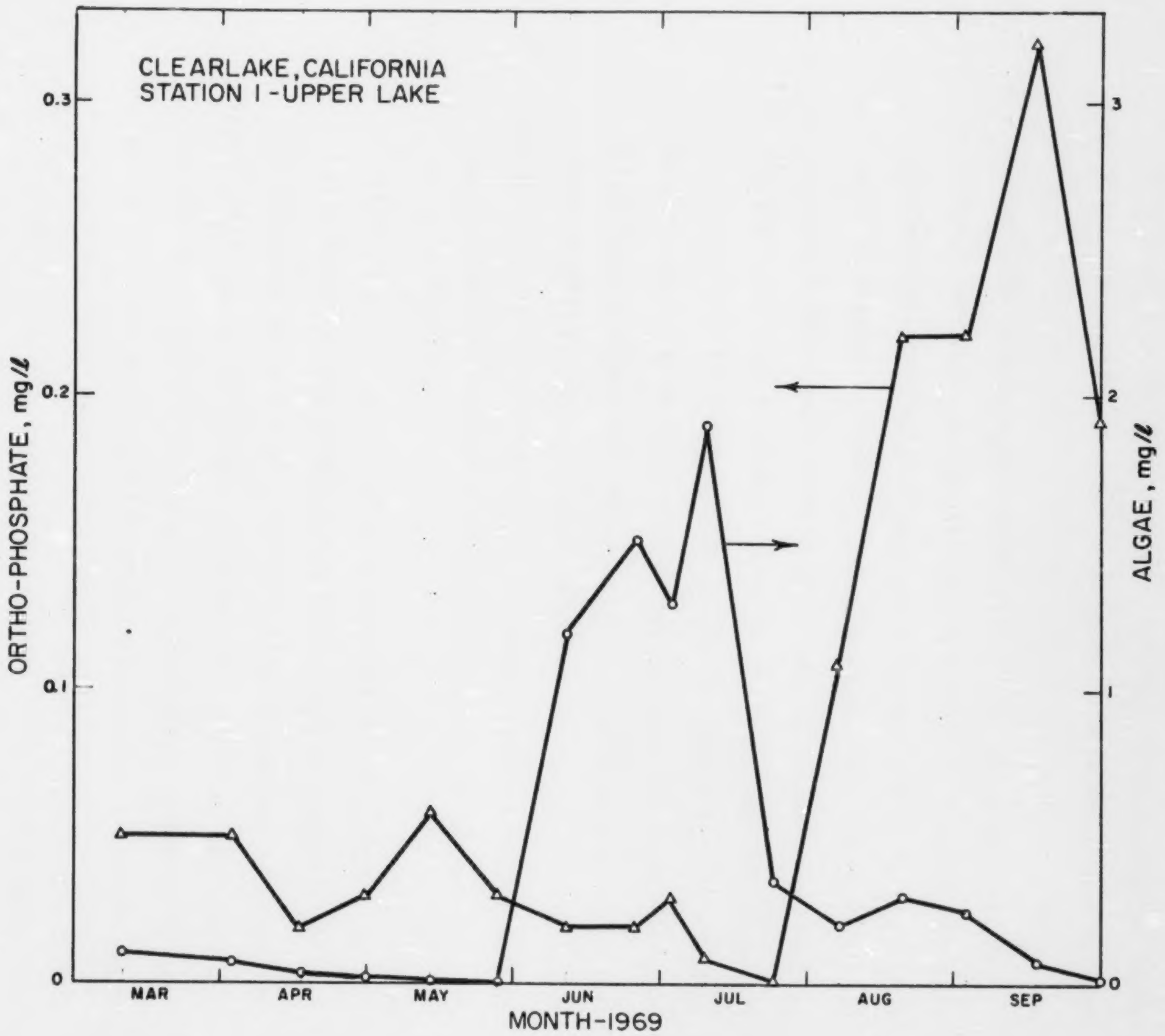


FIGURE 7 The relationship of ortho-phosphate and algal bloom as a function of time in the upper lake arm of Clear Lake

less phosphate in the silt would cause less phosphate to be released. However, similar but lesser releases did occur in both arms. An examination of Figure 8 for Lower Lake shows that three periods of phosphate depletion occurred - each corresponding to strong algal blooms. In each case phosphate was apparently quickly replenished from bottom deposits. It is interesting to note that an algal biomass of 9 mg/l initially depleted the Lower Arm of 0.03 mg/l of phosphate and that the indicated percentage phosphate in the algae is .03/9 = 0.33 percent phosphorus, a normal but slightly low value.

The relationship between soluble phosphate and algal growth in the surface water in the Oaks Arm is shown in Figure 9. Some phosphate depletion apparently occurred in April and May without algal growth, possibly indicating a form of precipitation or adsorption in silt. In July, a large algal bloom took up 0.05 mg/l phosphate. The algal concentration attained 10.8 mg/l and the indicated fraction of phosphate in the algae is 0.05/10.8 = 0.46%. A subsequent algal bloom did not deplete the soluble phospate because a strong release of phosphate from the bottom was apparently underway. It is remarkable that the August and September phosphate release in Upper Lake did not enhance the algal bloom, but actually appeared to suppress it. Such an anomalous relationship supports the theory that the same phenomena that releases benthal phosphate from the bottom muds also release other substances toxic to the algae inhibiting their subsequent blooms. Evidence is lacking that such a release-inhibition phenomena occurs in Lower Lake. Of course the Lower Lake muds are less likely to contain impurities since the water has been passed through a greater fraction of the lake before reaching Lower Lake and the water is "treated" by the various physical and biological processes that occur,

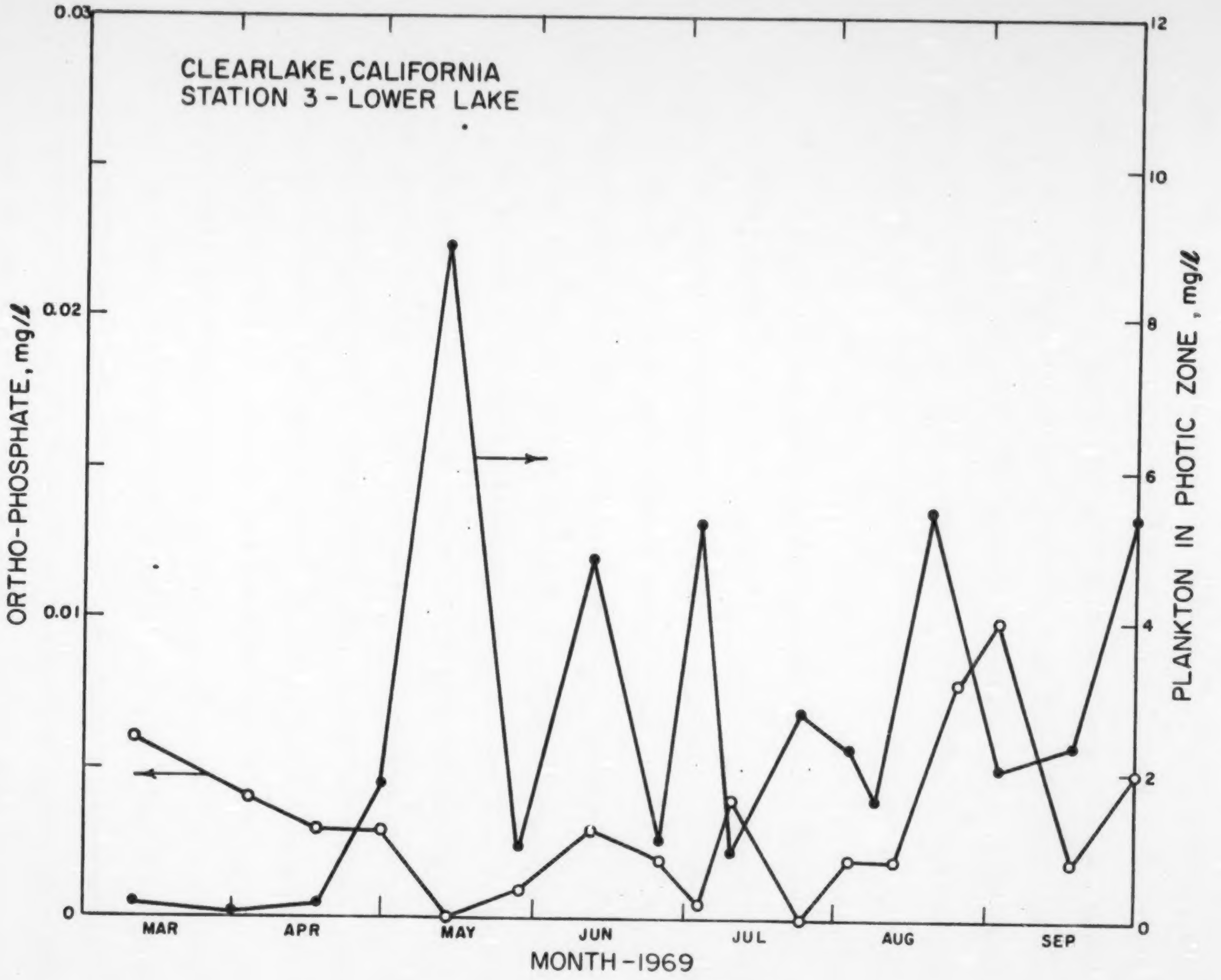


FIGURE 8 Relationship of ortho-phosphate and algal bloom as a function of time in the lower lake arm of Clear Lake

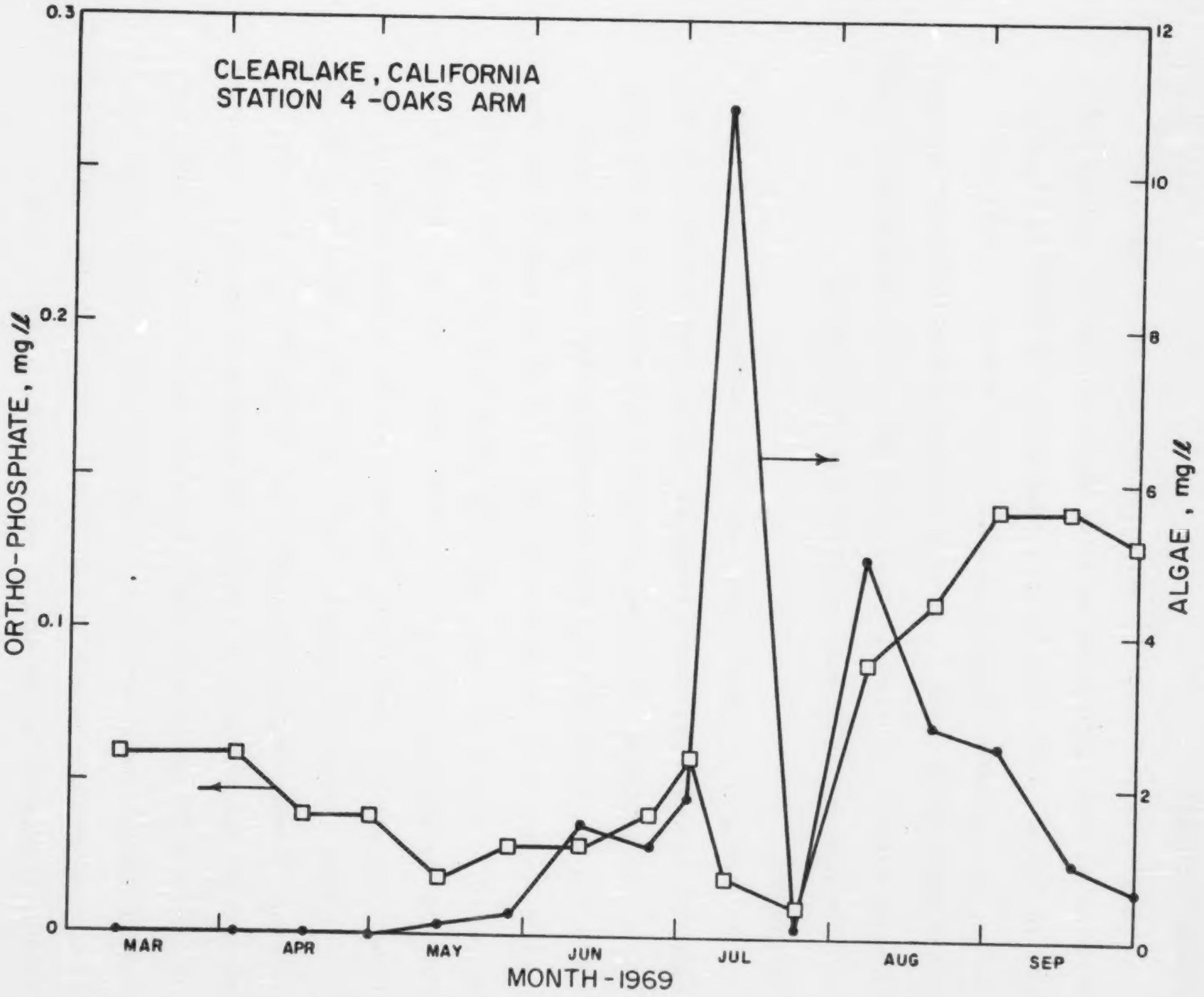


FIGURE 9 Relationship of ortho phosphate and algal bloom as a function of time for the Oaks arm of Clear Lake

prior to its entrance into Lower Lake.

GAONKAR'S STUDIES

The studies of Gaonkar(10) which followed the DWR studies, were conducted at five stations and at three depths per station from October, 1969 to October, 1970. Studied were temperature transparency, pH, alkalinity, algal biomass, Selenastrum algal growth potential (SAGP) and bottom mud volatile matter. The five stations sampled by Gaonkar are shown by Roman numerals in Figure 1 and his data for each of the parameters noted is reproduced in its entirety in Tables 9 to 17 inclusive.

Temperature

As indicated in Table 9, there was little difference (usually less than 3°C) between temperatures in the various stations and depths in the lake at the same time. There was evidence of stratification of the lake May through September, but the stratification was not strong or stable because the top to bottom differential of 5°, which occurred in May, was decreased to only 2° in July. Gaonkar's temperature data, like that of DWR, thus evidences a shallow body of water which tends to stratify in summer, but which is periodically destratified due to wind mixing.

Maximum temperature found by Gaonkar was 29.5° in the Lower Lake in June. Minimum temperature found by Gaonkar was 9.5°C in February. Gaonkar did not have data for January but a DWR study showed a temperature of 47°F or 8.5°C in January, 1965. Extrapolation of Gaonkar's data indicates a temperature of about 8.5°C in January. The 1965 DWR study indicated a temperature maximum in June of 80°F, slightly below Gaonkar's finding of 29.5°C. No DWR data is available for December, 1965.

TABLE 9 TEMPERATURE OF CLEAR LAKE WATER 1969-1970
in °C

Date	Station I			Station II			Station III			Station IV			Station V		
	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot
10/16/69	16.0	16.0	16.0	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.5	17.5	12.0	11.5	11.0
10/29/69	17.0	17.0	17.0	16.0	16.0	16.0	17.0	17.0	17.0	16.0	15.5	15.0	11.5	11.0	11.0
11/12/69	14.0	14.0	14.0	15.0	14.5	14.0	16.0	15.0	15.0	13.5	13.0	13.0	11.0	10.5	10.5
11/24/69	11.5	11.5	11.5	11.5	11.5	11.5	13.0	13.0	13.0	12.5	12.0	11.5	10.0	10.0	9.5
12/ 4/69	11.0	10.5	10.5	10.5	10.5	10.5	12.0	11.5	11.5	11.5	11.5	11.0	10.5	10.0	10.0
12/15/69	10.5	10.5	20.0	10.5	10.5	20.5	11.5	11.5	11.5	10.5	10.5	10.0	12.0	12.0	12.0
2/ 4/70	11.0	10.5	10.0	10.0	9.5	9.5	10.5	10.0	10.0	9.5	9.5	9.5	13.5	13.5	14.0
2/18/70	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.5	10.0	10.0	15.0	14.0	14.0
3/ 3/70	10.5	10.5	10.0	10.5	10.0	10.0	10.0	10.0	10.0	11.5	11.5	11.5	12.0	12.0	12.0
3/16/70	13.5	12.5	12.0	11.5	11.0	11.0	13.0	13.0	12.5	13.0	13.0	13.0	15.0	14.5	14.5
3/31/70	13.0	13.0	13.0	12.0	12.0	12.0	13.0	13.0	13.0	15.0	14.0	14.0	24.0	23.0	21.0
4/15/70	16.0	15.0	15.0	13.5	13.0	13.5	14.0	14.0	14.0	13.0	12.5	12.0	23.5	23.0	22.0
4/28/70	14.5	14.0	12.5	13.0	13.0	13.0	12.5	12.0	12.0	15.0	14.0	14.0	29.5	28.0	26.0
5/12/70	14.0	13.5	13.5	14.5	14.0	14.0	16.0	15.0	15.0	23.0	22.5	19.0	26.5	25.5	24.5
5/26/70	25.0	23.0	20.0	24.0	23.0	20.0	23.0	23.0	23.0	22.0	23.0	22.0	26.0	26.0	24.0
6/10/70	27.0	23.0	22.0	23.5	22.5	22.0	24.0	23.5	22.5	27.5	26.0	24.0	27.5	27.0	26.0
6/22/70	27.0	25.0	22.0	26.5	25.5	23.0	28.5	27.0	24.5	25.0	24.0	23.5	27.5	27.0	26.5
7/ 2/70	24.0	23.0	22.5	25.5	24.0	23.0	26.0	25.0	24.0	25.5	25.0	23.5	28.0	28.0	26.5
7/13/70	25.0	24.5	22.0	25.0	25.0	23.0	26.5	26.5	25.5	26.5	26.0	25.0	25.0	24.5	24.0
7/24/70	25.5	25.0	23.0	26.0	26.0	25.0	27.0	27.0	26.0	26.5	26.0	26.0	25.0	25.0	24.5
8/ 3/70	26.0	26.0	25.0	25.0	25.0	25.0	27.0	26.5	26.5	26.0	26.0	25.5	23.0	23.0	23.0
8/13/70	25.5	25.5	24.0	25.5	25.0	24.5	28.0	27.5	26.5	25.0	24.5	24.0	21.5	21.0	21.5
8/24/70	24.0	24.0	23.5	24.0	24.0	24.0	25.5	25.0	25.0	25.0	24.5	24.5	20.0	20.0	20.0
9/ 3/70	23.0	23.0	22.5	23.0	23.0	23.0	25.0	25.0	24.5	23.0	22.0	22.0	19.5	19.0	19.0
9/14/70	21.5	21.0	21.0	22.0	21.5	21.5	23.0	22.5	22.5	21.5	21.5	21.5	--	--	--
9/24/70	20.0	20.0	20.0	21.0	21.0	20.5	21.0	20.5	20.0	20.0	19.5	19.5	--	--	--
10/ 5/70	19.5	19.0	19.0	19.5	19.0	19.5	20.0	20.0	20.0	19.5	19.0	19.0	--	--	--
10/15/70	18.0	18.0	18.0	18.0	18.0	18.0	19.0	19.0	19.0	--	--	--	--	--	--

After Gaonkar (10)

Stratification of Clear Lake is accompanied by sedimentation of turbidity and growth of surface algae. Inasmuch as algae absorbs much more light than they use and convert to heat, there is a tendency to stabilize the stratification. However, wind mixing is sufficient to destroy the thermal difference and thus, occasional complete, virtually vertical mixing ensues. According to D. D. Gaillard's "Wave Action", the height of waves (h_w) in feet will be $h_w = 1.5f^{1/2} + 2.5 - f^{1/4}$ in which f is the fetch in nautical miles. For Clear Lake, one obtains wave heights between 5 and 6 feet (1.5 and 1.8 meters). Also according to Gaillard, wave velocity (v) in feet per second is $v = 5 + 2\ h_w$. Thus for Clear Lake we predict wave velocities between 15 and 17 feet per second (4.6 and 5.2 meters per second) near the surface. It seems likely that this process occurs at least once each month and perhaps twice each month in Clear Lake during the summer. Deep vertical mixing is indicated.

Transparency

Gaonkar's Secchi disc transparencies are shown in Table 10. According to these data, maximum transparencies occurred in the Lower Lake stations and minimum transparencies occurred in the Upper Lake station. Observed transparencies varied from 23 centimeters in the Upper Lake in February to 320 centimeters in the Lower Lake in July. February transparencies reflected the fact of soil turbidity in the water, whereas the July transparencies were inversely proportional to the concentration of algae. As indicated in Equation 1 (solved for x), the concentration of algae predicted by a light penetration of 320 centimeters would be about 1 mg/l.

It should be noted that Gaonkar's sampling stations were located near the center of the lake, whereas the major concentrations of surface algae tend to drift near the lake shore.

TABLE 10

SECCHI DISC TRANSPARENCY OF CLEAR LAKE WATER

(CENTIMETERS)

Date	Station I	Station II	Station III	Station IV	Station V
10/16/69	38	46	46	41	41
10/29/69	28	30	39	43	41
11/12/69	30	34	43	36	48
11/24/69	32	29	37	38	53
12/ 4/69	25	30	36	41	50
12/15/69	28	38	48	36	71
2/ 4/70	23	25	41	46	67
2/18/70	25	25	48	48	50
3/ 3/70	29	30	39	51	72
3/16/70	34	36	47	65	89
3/31/70	42	46	47	74	180
4/15/70	75	65	61	66	210
4/28/70	58	61	58	72	290
5/12/70	41	89	48	76	94
5/26/70	150	200	190	200	230
6/10/70	69	89	100	81	140
6/22/70	130	110	180	260	110
7/ 2/70	100	46	110	230	99
7/13/70	170	190	200	320	100
7/24/70	180	140	150	190	89
8/ 3/70	140	210	94	160	57
8/13/70	200	190	76	110	48
8/24/70	130	41	69	99	66
9/ 3/70	56	56	64	62	69
9/14/70	39	38	69	46	--
9/24/70	43	23	43	[illegible]	--
10/ 5/70	86	46	58	61	--
10/15/70	53	41	51	--	--

pH

Gaonkar's data for pH at the various depths and stations are presented in Table 11. A maximum pH of 9.3 was observed at Station III in early September and minimum pH of 7.5 was observed at Station I in February and at Station III in October. The lower pH in October is believed due to organic acid formation or CO_2 production in the lake bottom, whereas the lower pH of 7.5 in February is associated with rainwater runoff. The higher pH levels are associated with photosynthetic activity as will be discussed below.

Alkalinity

Gaonkar's alkalinity data for the lake is presented in Table 12. Alkalinity is presented in terms of mg/l as $CaCo_3$, 100 mg/l of $CaCo_3$ being equal to two equivalents of alkalinity as HCO_3 or CO_3. Assuming the alkalinity present is HCO_3, a change of 10 mg/l would indicate the uptake or release of about 2 mg of carbon. Inasmuch as most growing algae are about 45% carbon, a decrease of 10 mg of bicarbonate alkalinity would indicate the growth of about 4 mg of algae. As noted above, not all decreases in alkalinity indicate photosynthetic uptake. During the wet season, the lake was diluted with low alkalinity rainwater and runoff, with a proportional decrease in alkalinity. Thus, the decline in alkalinity at Station I from 120 on December 15 to 80 on February 4 was due primarily to dilution. The increase in alkalinity during the ensuing months probably resulted from a combination of evaporative concentration and organic decomposition in the lake. During the summer, oxidative decomposition, evaporative concentration and algal uptake were about balanced, so that alkalinity remained fairly constant at any given station. The mean alkalinity, however, increased from Station I to Station IV possibly indicating a slight excess of oxidation and

TABLE 11 pH OF CLEAR LAKE WATERS

Date	Station I			Station II			Station III			Station IV			Station V		
	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot
10/16/69	8.1	--	--	8.1	--	--	7.5	--	--	--	--	--	--	--	--
10/29/69	8.0	--	--	8.0	--	--	8.0	--	--	8.0	--	--	--	--	--
11/12/69	8.0	8.0	8.0	8.0	7.8	7.8	7.8	7.8	7.6	7.8	7.8	8.0	--	--	--
11/24/69	8.0	7.9	7.9	7.9	7.9	7.9	7.9	7.8	7.8	7.8	7.8	7.8	--	--	--
12/ 4/69	8.0	8.0	8.0	7.9	7.9	7.9	7.8	7.8	7.8	7.7	7.7	7.7	7.6	7.6	7.6
12/15/69	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.8	7.7	7.7	7.8	7.9	7.8	7.8	7.7
2/ 4/70	7.8	7.8	7.8	7.8	7.9	7.9	7.9	7.8	7.9	7.9	7.9	8.0	7.9	8.0	7.9
2/18/70	7.5	7.6	7.8	7.8	7.8	7.8	7.8	7.9	7.9	8.0	8.0	8.0	7.9	8.0	7.9
3/ 3/70	7.8	7.8	7.8	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.1	8.0	8.0	8.0	7.9
3/16/70	7.9	7.9	7.9	7.7	7.9	7.8	7.9	7.8	7.9	8.0	7.9	8.0	7.9	7.9	7.9
3/31/70	8.0	8.0	8.0	8.0	8.0	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9	7.9
4/15/70	7.7	7.7	7.7	7.7	7.7	7.7	7.8	7.9	7.9	7.9	7.9	7.9	8.0	8.0	7.9
6/10/70	8.2	--	--	8.2	--	--	8.3	--	--	8.3	--	--	8.5	--	--
6/22/70	8.9	8.8	8.4	8.8	8.8	8.5	8.8	8.8	8.4	8.8	8.7	8.3	8.6	8.6	8.3
7/ 2/70	9.0	9.0	8.8	9.2	9.1	8.7	9.1	9.1	8.9	8.6	8.6	8.5	9.0	8.8	8.5
7/13/70	9.1	9.1	8.5	9.0	9.0	8.6	9.1	9.1	8.9	9.0	9.0	8.6	9.0	9.0	8.5
7/24/70	8.8	8.8	8.5	8.9	8.8	8.5	9.0	9.0	8.8	8.7	8.6	8.5	9.0	8.9	8.5
8/ 3/70	9.0	9.0	8.8	8.8	8.7	8.7	9.1	9.1	8.9	8.9	8.7	8.6	9.0	9.0	8.6
8/13/70	8.9	8.8	8.7	9.0	9.0	8.7	9.4	9.3	9.0	9.0	8.7	8.8	9.1	9.0	8.6
8/24/70	8.6	8.6	8.7	8.6	8.6	8.6	9.0	8.9	8.9	8.9	8.9	8.7	8.8	8.7	8.7
9/ 3/70	9.0	9.0	8.8	9.0	9.0	8.9	9.3	9.2	9.1	9.2	.90	8.8	9.2	9.0	9.0
9/14/70	8.7	8.7	8.7	8.8	8.7	8.7	8.8	8.8	8.6	8.5	8.5	8.5	8.7	8.6	8.5
9/24/70	8.9	8.8	8.7	8.8	8.8	8.7	8.6	8.6	8.5	8.6	8.5	8.4	8.5	8.4	8.3
10/ 5/70	8.6	8.6	8.6	8.5	8.4	8.4	8.6	8.6	8.6	8.5	8.5	8.4	8.8	8.7	8.5
10/15/70	8.5	8.5	8.5	8.4	8.4	8.4	8.7	8.6	8.5	8.5	8.5	8.4	8.5	8.5	8.4

TABLE 12 ALKALINITY, mg/l ($CaCO_2$) OF CLEAR LAKE WATER

Date	Station I			Station II			Station III			Station IV			Station V		
	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot
10/16/69	119.0	--	--	116.5	--	--	117.5	--	--	--	--	--	--	--	--
10/29/69	115.0	--	--	115.5	--	--	117.5	--	--	118.5	--	--	--	--	--
11/12/69	117.5	115.5	115.5	115.5	117.5	116.5	115.5	119.5	117.5	118.5	115.5	--	--	--	--
11/24/69	115.5	115.5	115.5	115.5	115.5	115.5	116.5	116.5	118.5	118.5	118.5	119.5	--	--	--
12/ 4/69	116.5	116.5	117.5	116.5	117.5	118.5	116.5	117.5	118.5	119.5	119.5	119.5	120.0	122.0	112.0
12/15/69	120.0	120.0	120.0	120.0	120.0	121.0	120.0	120.0	120.0	123.0	123.0	123.0	124.0	123.0	124.0
2/ 4/70	83.0	83.0	89.0	92.0	93.0	93.0	104.0	103.0	104.0	106.0	106.0	108.0	111.0	111.0	111.0
2/18/70	88.0	89.0	88.0	91.0	90.0	90.0	105.0	105.0	104.0	107.0	107.0	106.0	109.0	109.0	110.0
3/ 3/70	88.0	88.0	87.0	91.0	91.0	92.0	101.0	101.0	101.0	104.0	104.0	104.0	108.0	108.0	108.0
3/16/70	91.0	89.0	88.0	93.0	93.0	94.0	96.0	97.0	97.0	102.0	102.0	102.0	106.0	106.0	107.0
3/31/70	93.0	91.0	90.0	93.0	90.0	94.0	97.0	98.0	97.0	101.0	102.0	103.0	104.0	104.0	105.0
4/15/70	88.0	93.0	93.0	96.0	97.0	96.0	98.0	97.0	96.0	104.0	103.0	103.0	105.0	107.0	105.0
6/10/70	107.0	--	--	109.0	--	--	105.0	--	--	104.0	--	--	101.0	--	--
6/22/70	103.0	104.0	103.0	104.0	104.0	106.0	107.0	106.0	112.0	106.0	108.0	111.0	111.0	111.0	112.0
7/ 2/70	104.0	106.0	105.0	105.0	105.0	108.0	105.0	105.0	107.0	112.0	110.0	110.0	110.0	109.0	109.0
7/13/70	109.0	--	--	109.0	--	--	109.0	--	--	112.0	--	--	110.0	--	--
7/24/70	103.0	108.0	108.0	106.0	106.0	108.0	106.0	106.0	108.0	108.0	108.0	108.0	107.0	110.0	110.0
8/ 3/70	104.0	107.5	105.5	105.0	105.5	106.5	104.5	104.5	102.0	108.5	108.5	108.5	108.5	110.1	107.5
8/13/70	108.0	108.0	109.0	108.0	109.0	110.0	109.0	109.0	109.0	110.0	109.0	110.0	111.0	111.5	112.5
8/24/70	109.0	110.5	109.5	108.5	108.5	111.5	110.5	108.5	108.5	112.5	109.5	109.5	110.5	108.5	108.5
9/ 3/70	108.5	110.5	109.5	108.5	109.5	109.0	109.5	107.5	109.5	111.5	113.5	112.5	109.5	111.5	111.5
9/14/70	110.5	110.5	112.5	110.5	108.5	110.5	106.7	107.7	107.7	112.5	110.5	111.5	113.5	111.5	113.5
9/24/70	110.5	111.5	109.5	110.5	112.5	111.5	110.5	109.5	110.5	109.5	111.5	111.5	112.5	111.5	112.5
10/ 5/70	112.5	111.5	112.5	113.5	113.5	114.5	114.5	113.5	113.5	114.5	114.5	114.5	117.5	117.5	118.5
10/15/70	115.5	114.5	113.5	114.5	114.5	114.5	114.5	114.5	114.5	116.5	115.5	115.5	118.0	117.5	116.5

concentration effects over photosynthetic effects during the period of observation.

Biomass

Gaonkar's estimations of biomass in the lake's waters are tabulated in Table 13. The data is the dry weight of volatile material retained on a millipore filter after filtration and corrected in proportion to observed inorganic turbidity for the same samples. According to Gaonkar, because of the variability of chlorophyll in the algae, this method of determining biomass was preferable to chlorophyll determination.

An overall view of the data indicates that surface biomass increased from Station I to Station V from a mean of about 8 mg/l to a mean of about 14 mg/l. At Station I, monthly mean biomass declined from about 12 mg/l in November to about 4 mg/l in March. It then increases linearly to a maximum of about 16 mg/l in September, after which it declined to less than 10 mg/l in October. Maximum observed biomass was 54 mg/l at Station V in June. Minimum biomass was 0 mg/l in Station I in March.

AGP

The *Selenastrum* algae growth potential (SAGP) of Clear Lake water was studied by Gaonkar and his data is presented in Table 14. Gaonkar found that the growth of *Selenastrum* used in his experiments was influenced mainly by nitrate nitrogen up to a level of 20 mg/l. The results of that experiment are shown in Figure 10.

In Figure 11, the maximum minimum annual mean SAGP values for Clear Lake water from five stations and three depths are portrayed. The mean value lakewide was found to be 19.3 mg/l.

TABLE 13 BIOMASS IN CLEAR LAKE WATER SAMPLES

(mg/L)

Date	Station I		Station II		Station III		Station IV		Station V	
	Surface	3-Meter	Surface	3-Meter	Surface	3-Meter	Surface	3-Meter	Surface	3-Meter
11/12/69	15.25	15.75	12.50	6.75	8.85	9.00	9.25	9.25	13.95	13.30
11/24/69	10.20	7.70	9.20	15.45	8.20	11.45	11.45	10.70	13.85	15.25
12/ 4/69	8.80	9.70	11.20	7.05	14.45	12.80	13.70	14.45	6.30	7.10
12/15/69	15.75	12.25	14.45	19.50	9.75	6.65	4.30	8.90	4.95	5.30
2/18/70	7.00	8.55	6.15	5.35	7.90	9.10	7.30	5.25	5.45	4.60
3/ 3/70	1.60	0.55	0.00	8.70	7.60	8.85	4.55	5.00	3.75	5.05
3/16/70	0.00	0.00	1.50	0.60	6.00	6.00	2.85	3.90	14.35	8.40
3/31/70	4.50	4.10	3.95	4.50	5.40	5.00	2.50	2.15	7.00	4.13
4/15/70	3.65	3.30	3.50	3.15	6.20	8.85	2.85	3.45	6.63	6.38
4/28/70	3.50	3.75	5.63	6.00	4.25	5.50	4.63	6.25	4.00	3.75
5/12/70	8.50	6.75	6.50	6.25	27.88	15.13	18.75	7.50	6.00	6.40
5/26/70	3.25	5.00	1.00	1.75	1.75	1.75	18.75	8.75	3.45	4.95
6/10/70	19.00	15.80	8.90	10.95	8.30	8.75	2.70	3.20	54.05	17.40
6/22/70	9.25	7.95	8.30	9.50	6.75	8.15	15.10	17.40	3.00	6.50
7/ 2/70	6.20	6.55	29.35	9.55	7.60	11.95	0.60	2.00	7.55	8.55
7/13/70	2.85	3.75	6.00	5.50	4.80	3.90	3.30	2.90	20.65	18.90
7/24/70	0.25	0.00	2.60	2.65	7.95	4.20	0.00	0.75	14.25	9.35
8/ 3/70	6.65	7.15	7.65	6.45	15.95	13.15	6.40	5.60	14.10	11.55
8/13/70	3.90	3.75	6.10	5.55	18.85	11.60	6.70	8.60	24.15	14.00
8/24/70	8.40	10.25	19.35	20.70	31.90	17.60	14.75	10.50	30.15	21.40
9/ 3/70	12.05	10.55	12.70	13.55	18.30	24.35	16.65	12.70	18.45	15.35
9/14/70	18.45	18.50	17.85	17.65	17.80	15.15	12.95	13.20	24.95	16.75
9/24/70	11.50	11.25	41.20	31.30	19.95	13.15	51.75	15.95	17.45	15.15
10/ 5/70	5.80	6.65	13.60	12.75	18.70	14.30	7.90	7.10	--	--
10/15/70	13.85	10.40	18.00	19.60	27.55	21.00	14.25	13.70	--	--

After Gaonkar (10)

TABLE 14 AGP OF CLEAR LAKE WATER SAMPLES (mg/1)

Date	Station I			Station II			Station III			Station IV			Station V		
	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot	Surf	3-M	Bot
12/ 4/69	13.05	18.45	18.20	20.50	21.50	32.30	24.50	26.00	27.30	27.80	30.10	30.20	29.70	26.80	26.60
12/15/69	12.40	6.80	7.10	9.80	9.50	10.30	11.10	11.30	10.00	13.40	11.00	9.70	10.40	10.40	14.50
2/ 4/70	12.55	10.65	11.15	7.85	6.65	11.05	14.55	11.65	12.75	11.65	11.55	12.15	8.35	12.25	12.15
2/18/70	13.05	20.55	34.55	42.95	16.55	12.05	13.35	8.75	15.95	16.65	19.35	22.55	21.25	24.25	18.65
3/ 3/70	1.45	10.35	2.15	11.45	12.65	9.15	17.55	27.45	16.25	25.25	7.65	17.75	10.35	19.75	15.55
3/16/70	6.00	8.70	9.00	15.90	21.90	19.95	12.95	18.10	18.05	20.60	19.10	35.25	15.50	21.35	18.20
3/31/70	9.65	15.30	16.00	29.65	25.15	33.10	12.95	22.35	19.30	22.15	15.60	28.35	11.50	22.70	9.55
4/15/70	10.70	13.60	11.75	31.20	17.75	18.85	17.80	24.35	19.30	20.60	17.00	27.20	25.35	24.15	22.45
4/28/70	29.75	26.00	16.75	38.75	26.25	22.00	20.75	21.50	21.50	27.75	31.50	28.75	16.75	30.50	20.75
5/12/70	15.75	15.75	13.00	19.50	30.75	23.50	15.25	16.75	16.75	17.25	9.75	9.75	17.00	14.75	16.25
5/26/70	8.75	8.25	16.00	7.50	8.25	13.75	9.25	10.25	18.00	6.50	6.25	17.75	7.25	5.25	10.00
6/10/70	4.40	8.40	20.70	16.70	18.85	23.30	12.00	12.65	11.30	10.10	12.50	12.50	6.25	12.50	8.10
6/22/70	4.90	9.15	31.50	6.90	10.95	13.70	15.95	12.25	28.85	10.30	8.85	22.70	8.75	11.95	19.30
7/ 2/70	7.00	9.25	13.90	10.15	9.75	18.80	11.45	11.40	20.60	16.20	18.10	21.40	12.15	10.50	17.55
7/13/70	7.45	8.70	19.50	9.55	8.80	28.75	11.45	12.50	22.05	7.80	9.55	37.05	8.35	7.10	44.95
7/24/70	6.80	7.15	23.40	5.60	7.20	23.55	5.95	6.80	14.15	9.50	13.85	16.15	8.00	7.20	19.25
3/ 3/70	12.45	11.10	18.95	14.85	15.85	15.95	15.40	9.15	21.70	11.15	8.75	21.15	11.15	10.70	18.95
8/13/70	6.85	11.70	24.25	13.55	8.65	22.35	17.60	10.20	16.30	10.30	12.25	11.20	8.75	11.70	17.80
8/24/70	11.80	14.40	18.20	16.15	20.00	18.50	14.85	17.65	19.55	13.55	13.00	15.65	11.85	10.60	13.90
9/ 3/70	9.55	12.00	14.10	14.25	12.45	13.70	11.40	12.30	13.25	10.05	14.20	22.15	12.15	10.10	13.20
9/14/70	8.30	9.75	12.15	11.20	12.00	12.40	11.25	13.90	17.55	14.50	16.30	18.85	11.25	13.20	15.60
9/24/70	15.70	15.80	20.90	19.90	13.40	18.00	23.00	24.80	28.20	18.80	20.00	26.00	15.60	18.30	22.40
10/ 5/70	14.25	13.80	17.05	18.75	15.70	24.30	13.05	13.05	14.50	13.35	13.55	13.30	9.15	8.40	14.70
10/15/70	20.65	25.25	26.40	27.10	28.70	26.90	16.00	19.30	21.90	22.30	20.60	18.40	17.20	17.70	15.70

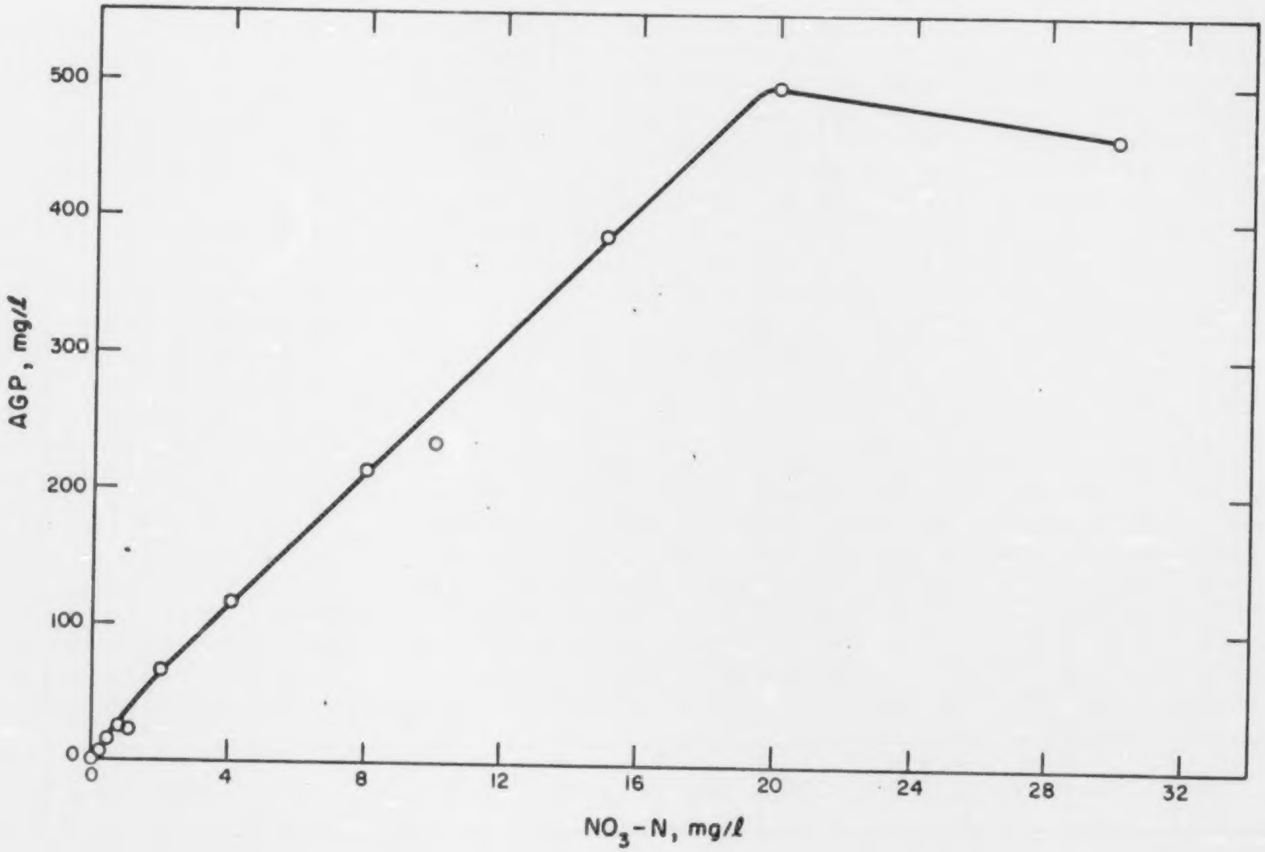


FIGURE-10 AGP(Selenastrum) with varying concentration of NO_3-N in Filtered Clear Lake water

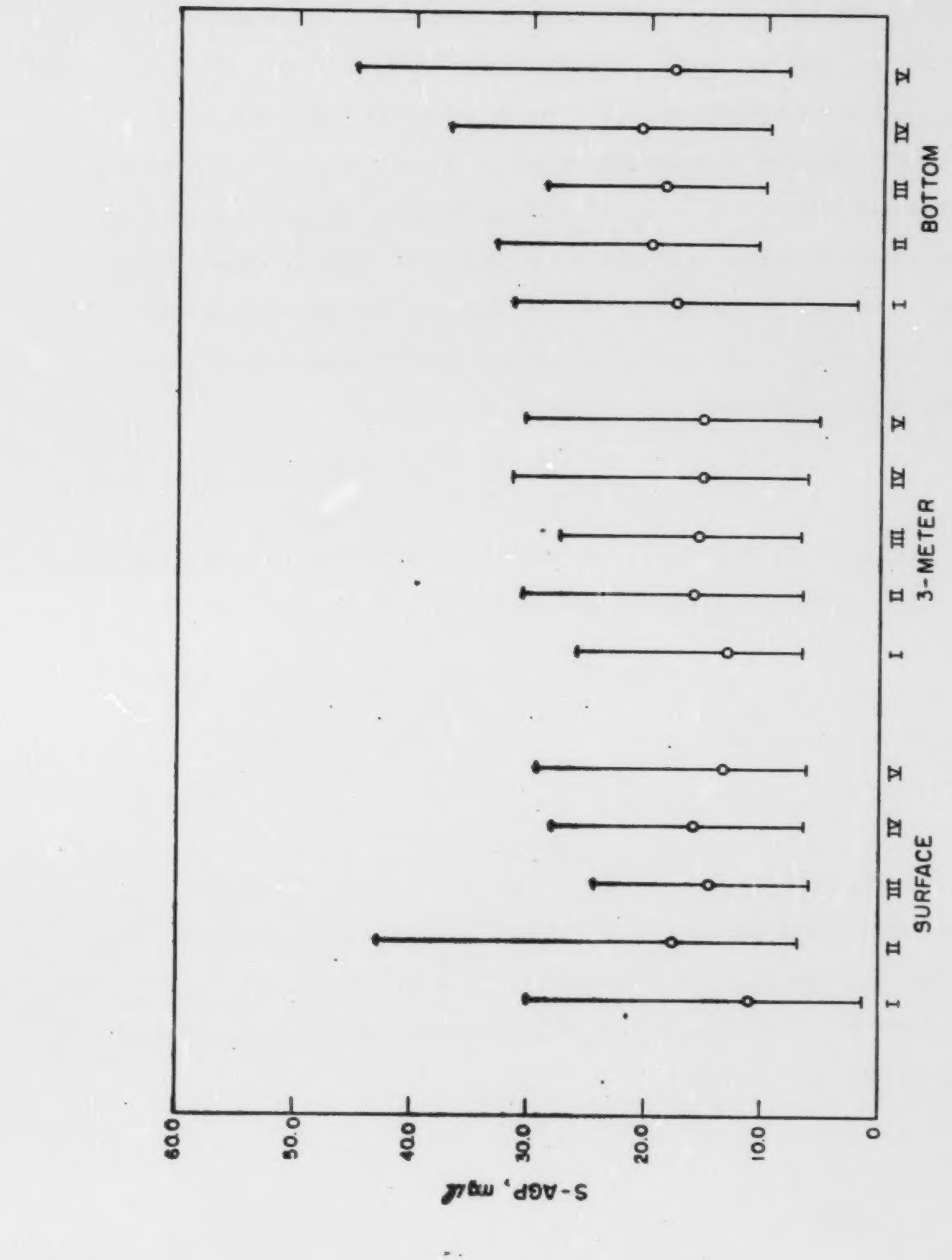


FIGURE-11 Maximum, minimum and annual mean S-AGP values of Clear Lake water from five stations and three depths (Dec 1969 to Oct 1970)

Theoretical yields

Consider an aliquot of lake water at any particular instant as modeled in Figure 12. The water will contain some nutrients which could potentially be converted to algae, x_r, some nutrients already converted and in the form of algae, x_a, and some nutrients, x_u, that are unavailable to algae under the conditions obtaining. Accordingly, there is in each aliquot of lake water, a total nutrient base $x_a + x_r + x_u$ which may be measured chemically. Here the reader should note that nutrients are expressed in terms of algae concentration or potential concentration. We then define a maximum algal growth potential (AGP) or x_p as the quality of algae which will grow when no factor other than available nutrient limits growth:

$$x_p = x_a + x_r \tag{2a}$$

and the fraction of the AGP actually in the form of algal biomass expressed as a percent is termed the yield, percentage Y, thus:

$$Y = \frac{x_a}{x_p} \times 100 \tag{2b}$$

or

$$Y = \frac{x_a}{x_a + x_r} \times 100 \tag{2c}$$

Gaonkar determined x_p values and Y values on the basis of equation 2b and data from corresponding aliquots of lake water having the analyses shown in Tables 13 and 14. The x_p values are shown in Table 15 and the Y values in Table 16. Gaonkar concluded that the overall mean x_p value for Clear Lake in 1970 was 19.3 mg/l.

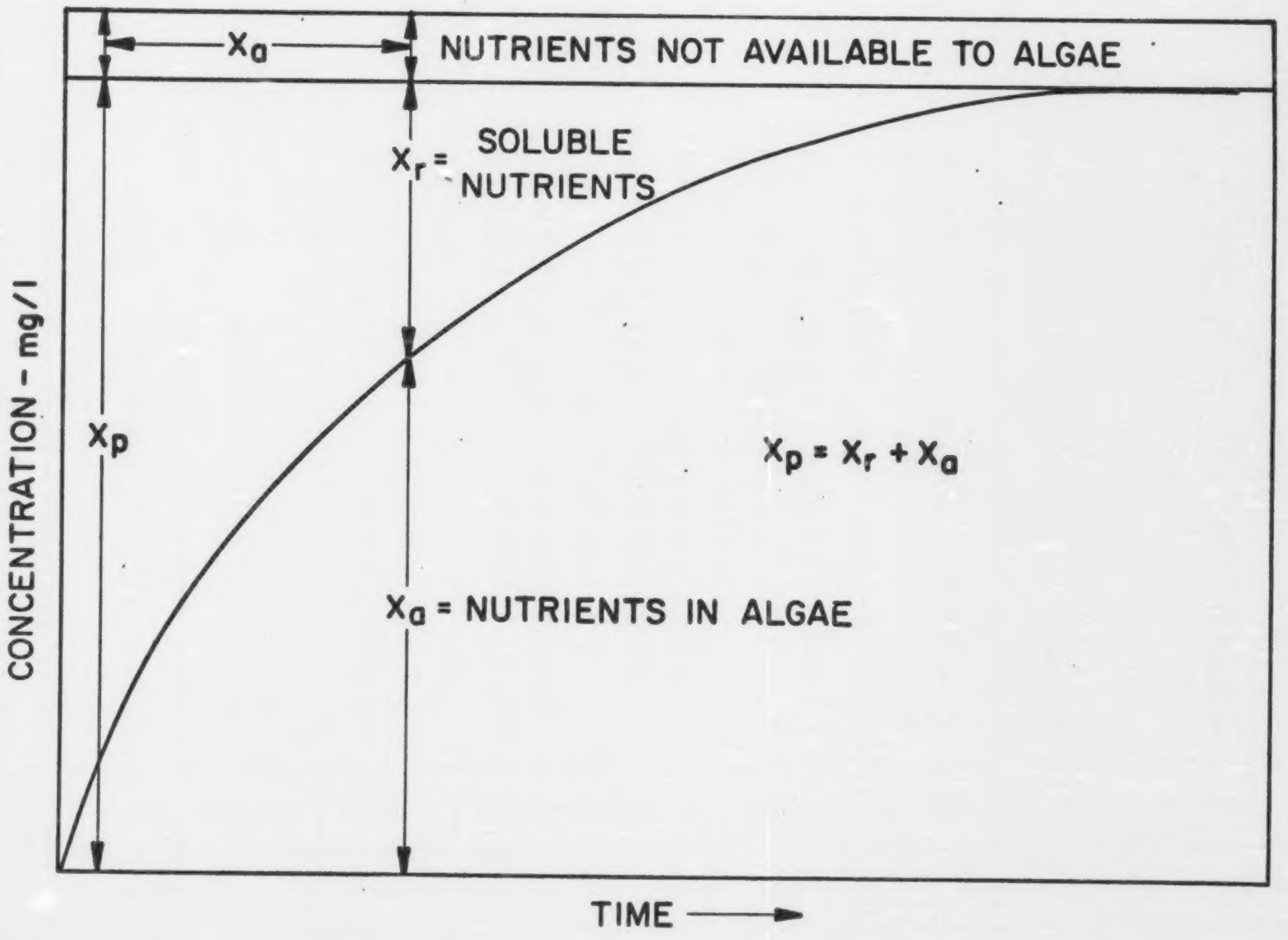


FIGURE 12 Idealized model of a total nutrient base in a small isolated volume of lake water

TABLE 15 AGP AND BIOMASS TOTALS

(mg/L)

Date	Station I		Station II		Station III		Station IV		Station V	
	Surface	3-Meter	Surface	3-Meter	Surface	3-Meter	Surface	3-Meter	Surface	3-Meter
12/ 4/69	21.85	28.15	31.70	28.55	38.95	38.80	41.50	44.55	43.65	40.10
12/15/69	28.15	19.05	24.25	29.00	20.85	17.95	17.70	19.90	24.25	25.65
2/18/70	20.05	29.10	49.10	21.90	21.25	17.85	23.95	24.60	27.55	31.35
3/ 3/70	3.05	10.90	11.45	21.35	25.15	36.30	29.80	12.65	15.30	25.05
3/16/70	6.00	8.70	17.40	22.50	18.95	24.10	23.45	23.00	20.95	22.80
3/31/70	14.15	19.40	33.60	29.65	18.35	27.35	24.65	17.75	15.25	27.75
4/15/70	14.35	16.90	34.70	20.90	24.00	33.20	23.45	20.45	39.70	32.55
4/28/70	33.25	29.75	44.38	32.25	25.00	27.00	32.38	37.75	23.75	34.63
5/12/70	24.25	22.50	26.00	37.00	43.13	31.88	36.00	17.25	23.63	21.13
5/26/70	12.00	13.25	8.50	10.00	11.00	12.00	25.25	15.00	11.25	9.00
6/10/70	23.40	24.20	25.60	29.50	20.30	21.40	12.80	15.70	12.25	18.90
6/22/70	14.15	17.10	15.20	20.45	22.70	20.40	25.40	26.25	12.20	16.90
7/ 2/70	13.20	15.80	39.50	19.30	19.05	23.35	16.80	20.10	66.20	27.90
7/13/70	10.30	12.45	15.55	14.30	16.25	16.40	11.10	12.45	11.35	13.60
7/24/70	7.05	7.15	8.20	9.85	13.90	11.00	9.50	14.60	15.55	15.75
8/ 3/70	19.10	18.25	22.50	22.30	31.35	22.30	17.55	24.35	31.80	29.60
8/13/70	10.75	15.45	19.65	14.20	36.45	21.80	17.00	20.85	23.00	21.05
8/24/70	20.20	24.65	35.50	40.70	46.75	35.25	28.30	23.50	25.95	22.15
9/ 3/70	21.60	22.55	26.95	26.00	29.70	36.65	26.70	26.90	36.30	24.10
9/14/70	26.75	28.25	29.05	29.65	29.05	29.05	27.45	29.50	41.40	34.60
9/24/70	27.20	27.05	61.10	44.70	42.95	37.95		35.95	34.05	33.65
10/ 5/70	20.05	20.45	32.35	28.45	31.75	27.35	21.25	20.65	34.10	25.15
10/15/70	34.50	35.65	45.10	48.30	43.55	40.30	36.55	34.30	34.65	32.85

TABLE 16A SURFACE DATA

Date	Station I		Station II		Station III		Station IV		Station V		
	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\overline{Y}$
	Ratio	Val	Ratio	Val	Ratio	Val	Ratio	Val	Ratio	Val	
12/ 4/69	$\frac{8.80}{21.85}$	.40	$\frac{11.20}{31.70}$	.35	$\frac{14.45}{38.95}$	.37	$\frac{13.70}{41.50}$	.33	$\frac{13.95}{43.65}$	.32	.35
12/15/69	$\frac{15.75}{28.15}$	.52	$\frac{14.45}{24.25}$	.57	$\frac{9.75}{20.85}$	.57	$\frac{4.30}{17.70}$	.24	$\frac{13.85}{24.25}$	.57	.47
2/18/70	$\frac{7.00}{20.05}$	.34	$\frac{6.15}{49.10}$	.13	$\frac{7.90}{21.25}$	.37	$\frac{7.30}{23.95}$	.30	$\frac{6.30}{27.55}$	.23	.27
3/ 3/70	$\frac{1.60}{3.05}$	.53	$\frac{0.00}{11.45}$	0	$\frac{7.60}{25.15}$	.30	$\frac{4.55}{29.80}$	.15	$\frac{4.95}{15.30}$	.32	.26
3/16/70	$\frac{0.00}{6.00}$	0	$\frac{1.50}{17.40}$	.09	$\frac{6.00}{18.95}$	.32	$\frac{2.85}{23.45}$	.12	$\frac{5.45}{20.95}$	.26	.16
3/31/70	$\frac{4.50}{14.15}$	.32	$\frac{3.95}{33.60}$	.12	$\frac{5.40}{18.35}$	.29	$\frac{2.50}{24.65}$	.10	$\frac{3.75}{15.25}$	.25	.22
4/15/70	$\frac{3.65}{14.35}$	.25	$\frac{3.50}{34.70}$	.10	$\frac{6.20}{24.00}$	.26	$\frac{2.85}{23.45}$	.12	$\frac{14.35}{39.70}$	.36	.22
4/28/70	$\frac{3.50}{33.25}$	.10	$\frac{5\ 63}{44.38}$	.13	$\frac{4.25}{25.00}$	.17	$\frac{4.63}{32.38}$	.14	$\frac{7.00}{23.75}$	.29	.17
5/28/70	$\frac{8.50}{24.25}$	.36	$\frac{6.50}{26.00}$	.25	$\frac{27.88}{43.13}$	.65	$\frac{18.75}{36.00}$	.52	$\frac{6.63}{23.63}$	.28	.41
5/26/70	$\frac{3.25}{12.00}$	.27	$\frac{1.00}{8.50}$	.12	$\frac{1.75}{11.00}$	.16	$\frac{18.75}{25.25}$	.74	$\frac{4.00}{11.25}$	.36	.33
6/10/70	$\frac{19.00}{23.40}$	.81	$\frac{8.90}{25.60}$	.35	$\frac{8.30}{20.30}$	.41	$\frac{2.70}{12.80}$	.21	$\frac{6.00}{12.25}$	.49	.45
6/22/70	$\frac{9.25}{14.15}$	.66	$\frac{8.30}{15.20}$	.55	$\frac{6.75}{22.70}$	.30	$\frac{15.10}{25.40}$	.59	$\frac{3.45}{12.20}$	.28	.48
7/ 2/70	$\frac{6.20}{13.20}$	.17	$\frac{29.35}{39.50}$	.74	$\frac{7.60}{19.05}$	.40	$\frac{0.60}{16.80}$	.04	$\frac{54.05}{66.20}$	.82	.49
7/13/70	$\frac{2.85}{10.30}$	.28	$\frac{6.00}{15.55}$	.39	$\frac{4.80}{16.25}$	.30	$\frac{3.30}{11.10}$	.30	$\frac{3.00}{11.35}$	.26	.25
7/24/70	$\frac{0.25}{7.05}$	.04	$\frac{2.60}{8.20}$	.32	$\frac{7.95}{13.90}$	.57	$\frac{0.00}{9.50}$	0	$\frac{7.55}{15.55}$	.49	.28
8/ 3/70	$\frac{6.65}{19.10}$	.35	$\frac{7.65}{22.50}$	.34	$\frac{15.95}{31.35}$	.51	$\frac{6.40}{17.55}$	.36	$\frac{20.65}{31.80}$	.65	.44
8/13/70	$\frac{3.90}{10.75}$	.36	$\frac{6.10}{19.65}$	.31	$\frac{18.85}{36.45}$	.52	$\frac{6.70}{17.00}$	.39	$\frac{14.25}{23.00}$	.62	.44
8/24/70	$\frac{8.40}{20.20}$	.42	$\frac{19.35}{35.50}$	.54	$\frac{31.90}{46.75}$	.68	$\frac{14.75}{28.30}$	.52	$\frac{14.10}{25.95}$	.54	.54
9/ 3/70	$\frac{12.05}{21.60}$	.58	$\frac{12.70}{26.95}$	.47	$\frac{18.30}{29.70}$	.62	$\frac{16.65}{26.70}$	.62	$\frac{24.15}{36.30}$	.67	.57
9/14/70	$\frac{18.45}{26.75}$	.69	$\frac{17.85}{29.05}$	.61	$\frac{17.80}{29.05}$	.62	$\frac{12.95}{27.45}$	.47	$\frac{30.15}{41.40}$	.73	.62
9/24/70	$\frac{11.50}{27.20}$	.42	$\frac{41.20}{61.10}$	.67	$\frac{19.95}{42.95}$	.46	$\frac{51.75}{70.55}$	.73	$\frac{18.45}{34.05}$	.54	.56
10/ 5/70	$\frac{5.80}{20.05}$	.29	$\frac{13.60}{37.35}$	.42	$\frac{18.70}{31.75}$	.59	$\frac{7.90}{21.25}$	.37	$\frac{24.95}{34.10}$	.73	.48
10/15/70	$\frac{13.85}{34.50}$	.40	$\frac{18.00}{45.10}$	.40	$\frac{27.55}{43.55}$	.63	$\frac{14.25}{36.55}$	.39	$\frac{17.45}{34.65}$	.50	.46

TABLE 16B 3-METER DATA

Date	Station I		Station II		Station III		Station IV		Station V		
	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\frac{X_a}{X_p}$	Y	$\bar{Y}$
	Ratio	Val	Ratio	Val	Ratio	Val	Ratio	Val	Ratio	Val	
12/ 4/69	$\frac{9.70}{28.15}$	.34	$\frac{7.05}{28.55}$	.25	$\frac{12.80}{38.80}$	.33	$\frac{14.45}{44.55}$	.32	$\frac{13.30}{40.10}$	.33	.31
12/15/69	$\frac{12.25}{19.05}$	.64	$\frac{19.50}{29.00}$	.67	$\frac{6.65}{17.95}$	.37	$\frac{8.90}{19.90}$	.45	$\frac{15.25}{25.65}$	.59	.54
2/18/70	$\frac{8.55}{29.10}$	.29	$\frac{5.35}{21.90}$	.24	$\frac{9.10}{17.85}$	.51	$\frac{5.25}{24.60}$	.21	$\frac{7.10}{31.35}$	.23	.30
3/ 3/70	$\frac{0.55}{10.90}$	.05	$\frac{8.70}{21.35}$	.41	$\frac{8.85}{36.30}$	.24	$\frac{5.00}{12.65}$	.40	$\frac{5.30}{25.05}$	.21	.26
3/16/70	$\frac{0.00}{8.70}$	0	$\frac{0.60}{22.50}$	.03	$\frac{6.00}{24.10}$	.25	$\frac{3.90}{23.00}$	.17	$\frac{4.60}{22.80}$	.20	.13
3/31/70	$\frac{4.10}{19.40}$	.21	$\frac{4.50}{29.65}$	.15	$\frac{5.00}{27.35}$	.18	$\frac{2.15}{17.75}$	.12	$\frac{5.05}{27.75}$	.18	.17
4/15/70	$\frac{3.30}{16.90}$	.20	$\frac{3.15}{20.90}$	.15	$\frac{8.85}{33.20}$	.27	$\frac{3.45}{20.45}$	.17	$\frac{8.40}{32.55}$	.26	.21
4/28/70	$\frac{3.75}{29.75}$	.13	$\frac{6.00}{32.25}$	.19	$\frac{5.50}{27.00}$	.20	$\frac{6.25}{37.75}$	.17	$\frac{4.13}{34.63}$	.12	.16
5/12/70	$\frac{6.75}{22.50}$	.30	$\frac{6.25}{37.00}$	.17	$\frac{15.13}{31.88}$	.47	$\frac{7.50}{17.25}$	.43	$\frac{6.38}{21.13}$	.30	.33
5/26/70	$\frac{5.00}{13.25}$	.38	$\frac{1.75}{10.00}$	.18	$\frac{1.75}{12.00}$	.15	$\frac{8.75}{15.00}$	.58	$\frac{3.75}{9.00}$	.42	.34
6/10/70	$\frac{15.80}{24.20}$	.65	$\frac{10.65}{29.50}$	.36	$\frac{8.75}{21.40}$	.41	$\frac{3.20}{15.70}$	.20	$\frac{6.40}{18.90}$	.34	.39
6/22/70	$\frac{7.95}{17.10}$	.46	$\frac{9.50}{20.45}$	.46	$\frac{8.15}{20.40}$	.40	$\frac{17.40}{26.25}$	.66	$\frac{4.95}{16.90}$	.29	.45
7/ 2/70	$\frac{6.55}{15.80}$	.41	$\frac{9.55}{19.30}$	.49	$\frac{11.95}{23.35}$	.51	$\frac{2.00}{20.10}$	.01	$\frac{17.40}{27.90}$	.62	.41
7/13/70	$\frac{3.75}{12.45}$	.30	$\frac{5.50}{14.30}$	.38	$\frac{3.90}{16.40}$	.24	$\frac{2.90}{13.45}$	.22	$\frac{6.50}{13.60}$	.48	.32
7/24/70	$\frac{0.00}{7.15}$	0	$\frac{2.65}{9.85}$	.27	$\frac{4.20}{11.00}$	.38	$\frac{0.75}{14.60}$	.05	$\frac{8.55}{15.75}$	.54	.25
8/ 3/70	$\frac{7.15}{18.25}$	.39	$\frac{6.45}{22.30}$	.29	$\frac{13.15}{22.30}$	.59	$\frac{5.60}{24.35}$	.23	$\frac{18.90}{29.60}$	.64	.43
8/13/70	$\frac{3.75}{15.45}$	.24	$\frac{5.55}{14.20}$	.39	$\frac{11.60}{21.80}$	.53	$\frac{8.60}{20.85}$	.41	$\frac{9.35}{21.05}$	.44	.40
8/24/70	$\frac{10.25}{24.65}$	.42	$\frac{20.70}{40.70}$	.51	$\frac{17.60}{35.25}$	.50	$\frac{10.50}{23.50}$	.45	$\frac{11.55}{22.15}$	.52	.48
9/ 3/70	$\frac{10.55}{22.55}$	.47	$\frac{13.55}{26.00}$	.52	$\frac{24.35}{36.65}$	.66	$\frac{12.70}{26.90}$	.47	$\frac{14.00}{24.10}$	.58	.54
9/14/70	$\frac{18.50}{28.25}$	.65	$\frac{17.65}{29.65}$	.60	$\frac{15.15}{29.05}$	.52	$\frac{13.20}{29.50}$	.45	$\frac{21.40}{34.60}$	.62	.57
9/24/70	$\frac{11.25}{27.05}$	.42	$\frac{31.30}{44.70}$	.70	$\frac{13.15}{37.95}$	.35	$\frac{15.95}{35.95}$	.44	$\frac{15.35}{33.65}$	.46	.47
10/ 5/70	$\frac{6.65}{20.45}$	.33	$\frac{12.75}{28.45}$	.45	$\frac{14.30}{27.35}$	.52	$\frac{7.10}{20.65}$	.34	$\frac{16.75}{25.15}$	.67	.46
10/15/70	$\frac{10.40}{35.65}$	.29	$\frac{19.60}{48.30}$	.41	$\frac{21.00}{40.30}$	.52	$\frac{13.70}{34.30}$	.41	$\frac{15.15}{32.85}$	.46	.42

Correlations

In further use of Gaonkar's data, it is worthwhile to examine the interrelations of the several parameters which he observed. As is often the case in natural systems, great variations occurred in each parameter and consequently general correlations can only be revealed by lengthy statistical analysis or by plotting all pertinent interelated data. Inasmuch as many of the interrelations are revealed graphically to be fairly weak, a statistical analysis does not seem to be warranted, and consequently only a visual qualitative analysis of the plotted data will be made.

pH and Temperature

The relationship between pH and temperature in surface samples is plotted in Figure 13. A linear relationship is apparent in the figure. There is a well known subtle effect of temperature on pH which amounts to about 0.01 pH unit per degree C, whereas in Figure 13, the difference in pH at 9.5°C and 29°C extends two full pH units, from about 7.6 to about pH 9.6. An interpretation of this relationship is that under low temperature, winter conditions, the lake receives substantial amounts of rain water and stream runoff, containing relatively large amount of turbidity and free CO_2, depressing the pH. However, as the lake warms in the spring, the turbidity decreases and algae grow, extracting CO_2 from the water and causing an upward shift in the pH. Later, in the fall, as the lake cools, photosynthetic activity is again restricted by temperature and turbidity and is accompanied by continuous organic decomposition and the pH declines. The level of pH is thus an indication of the relative degree of photosynthetic activity and decomposition activity, as well as

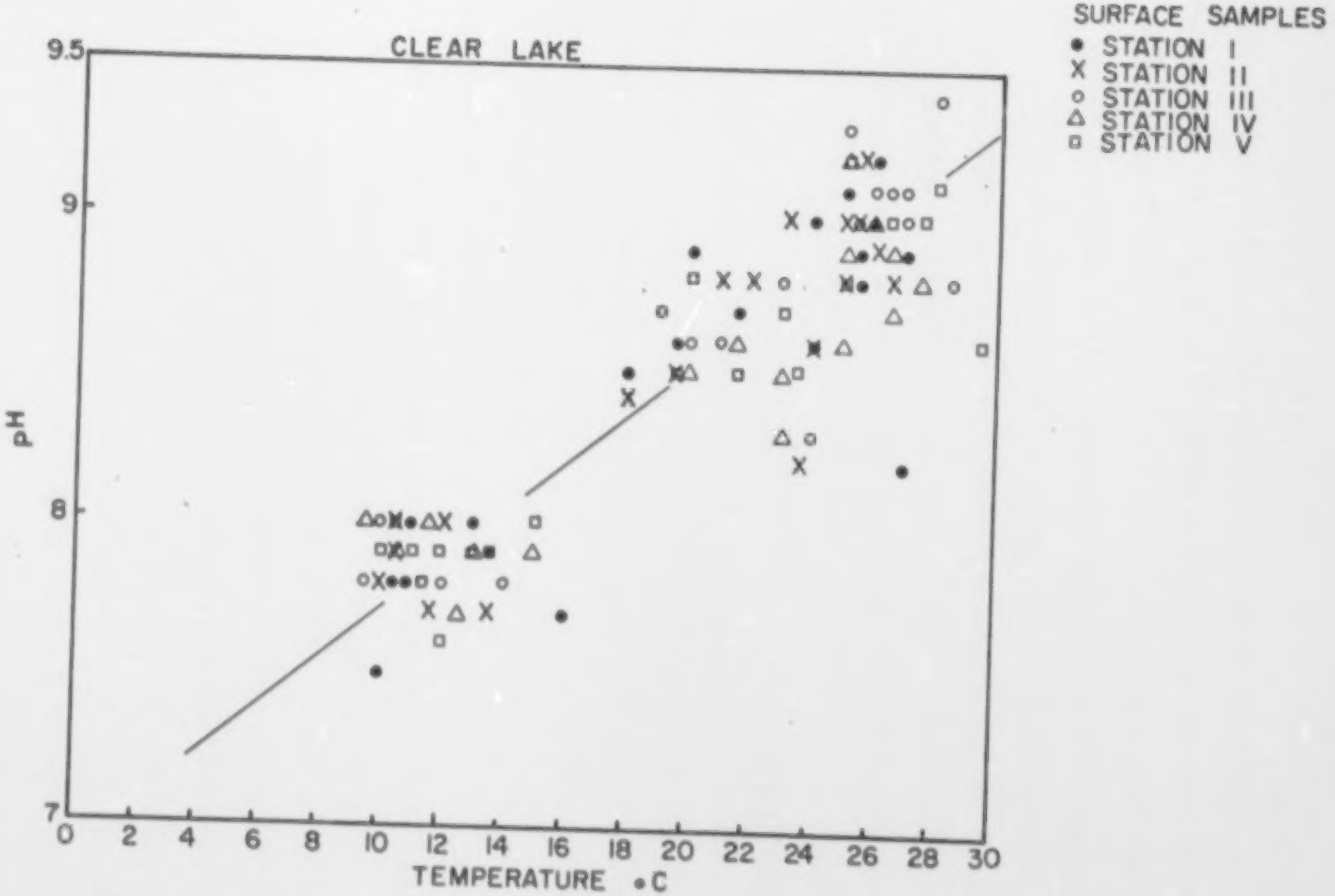


FIGURE 13 Relationship between pH and temperature in Clear Lake

of rain and runoff dilution and evaporative concentration, occurring in the lake.

pH and Alkalinity

It is not possible by pH measurements alone to distinguish which of the two factors, physical dilution or biological activity, brings about the change in pH. However, if pH and alkalinity are plotted simultaneously, it is possible to distinguish between physical dilution and biological change. In Figure 14, pH is plotted versus alkalinity for the lake observations. It is clear from this figure that there are two zones involved, one in which alkalinity declined as pH increased. The first change in alkalinity with little change in pH clearly resulted from a simple dilution or concentration of the lake water with rain and flood water, or by evaporative concentration. Involved were changes of alkalinity from about 120 mg/l of $CaCo_3$ to about 80 mg/l as $CaCO_3$. If this change resulted from dilution, it would correspond to a displacement of about one third of the higher alkalinity water in the lake, with lower alkalinity rainwater and runoff. The second change in alkalinity with increasing pH was from about 122 mg/l to about 105 mg/l as $CaCO_3$; a change of 17 mg/l or $\frac{17}{50} = 0.3$ meq/l. If this change was due to photosynthetic uptake from bicarbonate the maximum change was approximately 20 mg/l of HCO_3, indicating the uptake of 4 mg/l of carbon. If the algae involved in uptake were 40% carbon, the maximum increase in algae due to this degree of uptake would be about 10 mg/l. The change in pH due to photosynthetic activity was from 7.78 to about 9.4. Although alkalinity could have declined due to precipitation of $CaCo_3$, this probably did not occur to a significant extent because there is no evidence of a discontinuity in the pH vs alkalinity curve at pH 9.2.

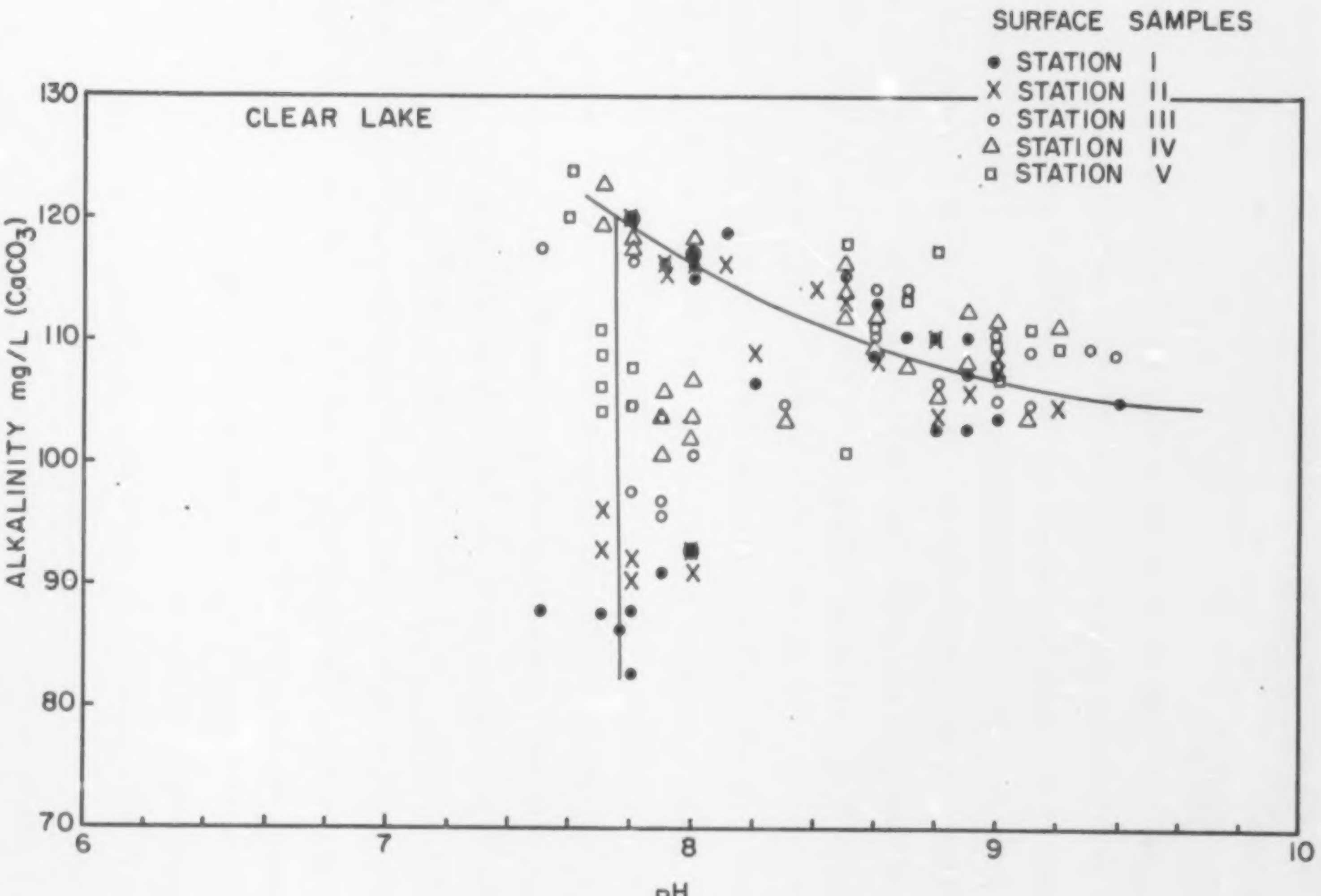


FIGURE 14 Relationship between pH and alkalinity in Clear Lake

Alkalinity and Temperature

The general relationships between pH and alkalinity in Clear Lake noted above are borne out by the relationship between alkalinity and temperature shown in Figure 15. It is again apparent in this figure that there is a zone in which alkalinity tended to change a great deal with little change in temperature and a zone in which alkalinity declined with increasing temperature. The change in alkalinity with little change in temperature is attributed to dilution of the lake water with lower alkalinity runoff and rainwater whereas the decline with increasing temperature is again related to photosynthetic activity.

Transparency and pH

Transparency and pH relationships are shown in Figure 16. Again two zones are evident -- one in which transparency changes greatly with little change in pH and one in which transparency remains constant or tends to decline slightly with increasing pH.

Species Effects on Transparency

Gaonkar in his dissertation notes that *Aphanizomenon* in growing had a "clarifying" effect on the water in that turbidity decreased somewhat with *Aphanizomenon* growth. Thus the change in transparency with algal growth in Clear Lake is a more complex phenomenon than modeled in Equation 1 which predicts that other factors being equal transparency is decreased by the algae concentration. Of course other factors are not equal because inorganic turbidity and the type of algae as well as the amount of algae are continuously changing. Gaonkar(10) explained his finding that transparency increased with increasing algae concentration by noting that clumps of *Aphanizomenon* were in a matrix of virturally clear water whereas in the

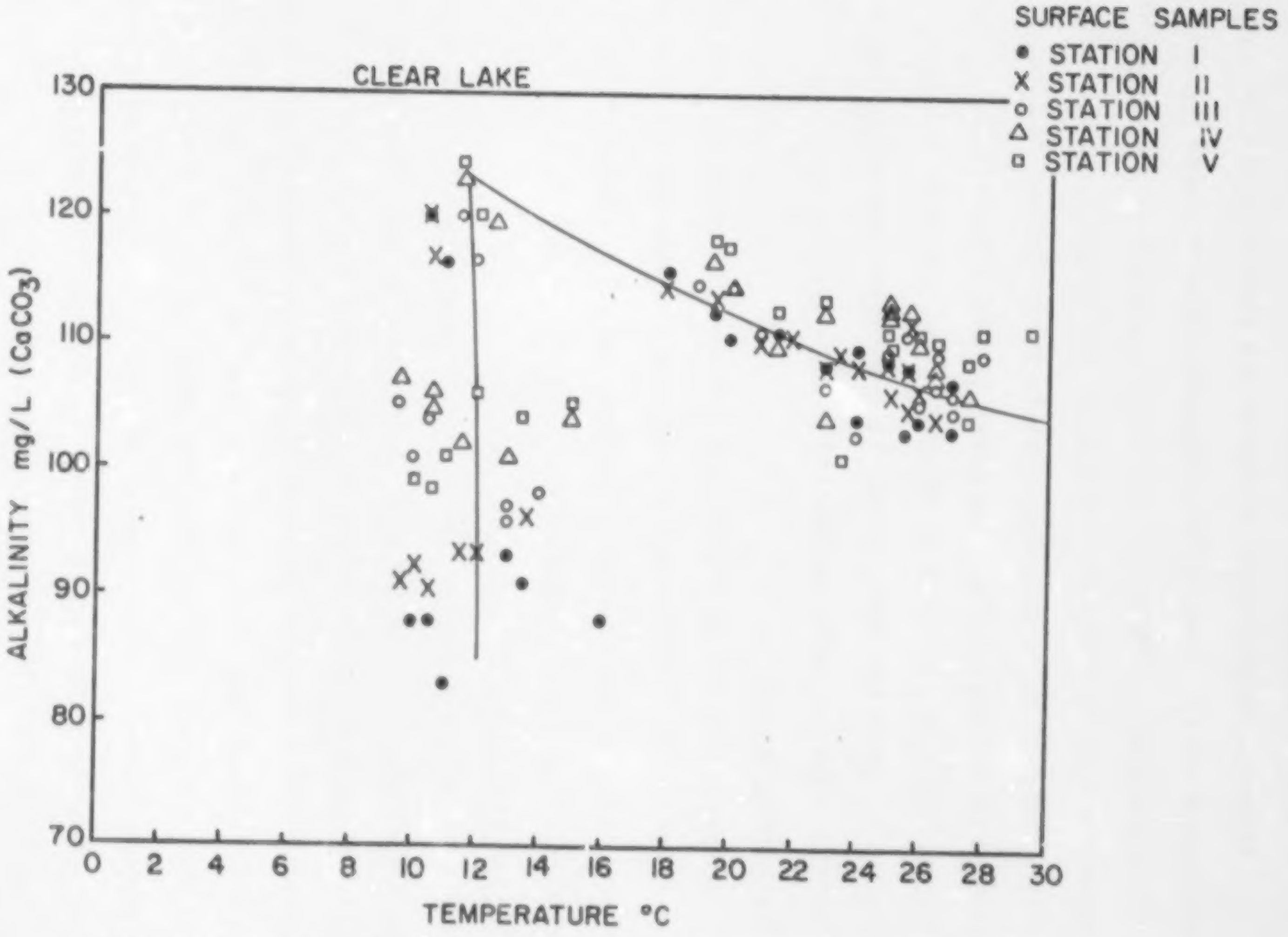


FIGURE 15 Relationship between alkalinity and temperature in Clear Lake

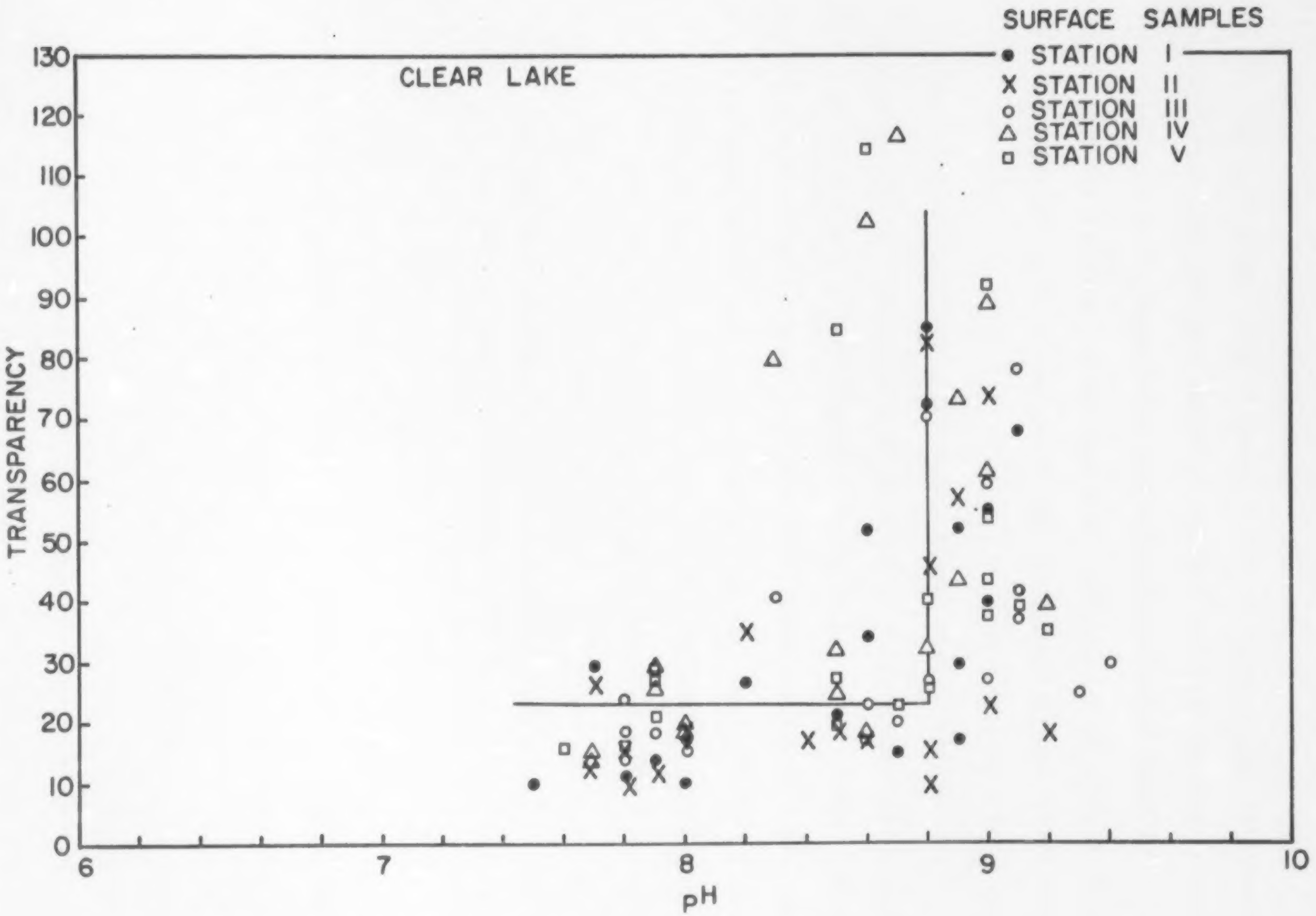


FIGURE 16 Relationship between pH and transparency in Clear Lake

absence of *Aphanizomenon* or the presence of other types of algae, the matrix water tended to be turbid. It seems from the data that *Aphanizomenon* growth was indeed accompanied by clarification of the surrounding water perhaps by flocculation or adsorption of suspended colloids, but this effect was confounded by wind mixing which increased inorganic turbidity from time to time.

The peculiar clarification associated with *Aphanizomenon* growth apparently did not occur in the case of algae other than *Aphanizomenon*. Gaonkar maintained a record of the several kinds of algae predominant in the lake at different times. His data are shown in Table 17. It is apparent from the table that *Microcystis* and *Anabaena* predominated over *Aphanizomenon* particularly during the warmer months, and apparently Equation 1 was more valid for *Aphanizomenon* than the others.

TABLE 17

Occurrence of *Aphanizomenon*, *Microcystis* and *Anabaena*
in Clear Lake During Various Periods

June 1970	July 1970	Aug 1970	Sept 1970	Oct 1970
Aphanizomenon	*Aphanizomenon*	*Microcystis*	*Microcystis*	*Microcystis*
(predominates)	*Microcystis*	*Anabaena*	*Anabaena*	*Anabaena*
				Aphanizomenon

Biomass and Temperature

A plot of biomass vs temperature is shown in Figure 17. These data indicate that at least two distinguishable zones are involved. One zone in which biomass tended to increase with temperature and one zone in which biomass declined with increasing temperature. A comparison of Figure 17

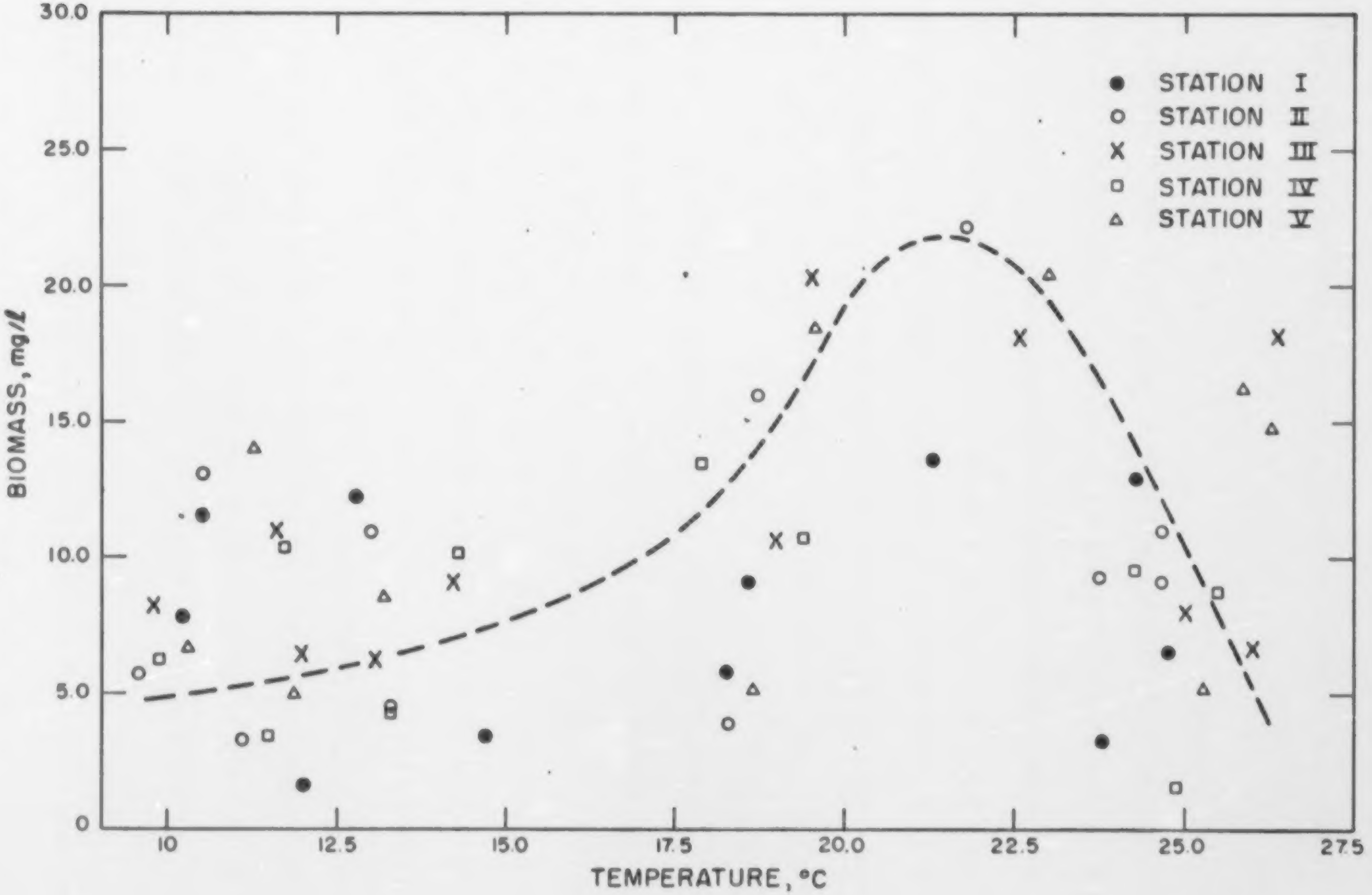


FIGURE 17 Relationship between biomass and temperature of Clear Lake water

and Table 17, shows that Aphanizomenon was more associated with lower temperature in the lake than were the other two species, and consequently, Aphanizomenon was indeed associated with the anomalously high light penetration.

Biomass and Transparency

A comparison of biomass and transparency in Figure 18 again indicates two zones - one in which transparency increases with biomass (contrary to Equation 1) and one in which transparency declines with biomass as predicted by Equation 1. While no direct cause-effect relationship can be drawn from the scattered data, one again obtains the distinct impression that Aphanizomenon is the organism associated with the observed anomalous increase in light penetration with increasing biomass.

Biomass and pH

The relationship between surface biomass and pH is shown in Figure 19. As might be expected, there is a distinct positive correlation between the two factors, but variations in biomass at a given pH is quite large. The higher biomass for pH 8.4 to pH 9.2 occurred under summer conditions and involved several species of algae whereas the lower biomass for pH 7.8 to 8.0 occurred under cool conditions and involved mainly Aphanizomenon.

Selenastrum AGP and Temperature

The Selenastrum algal growth potentials (SAGP) shown in Table 14 can also be related to several of the observed environmental factors through graphic analysis. Figure 20 is a plot of the SAGP of surface water, related to temperature at all stations in Clear Lake. In the figure, there appear to be two distinct temperature zones; from about 9.0^{o} to about 13°C in which the SAGP increases with temperature and from 13°C to 26°C in which SAGP tends to decline or remain constant with temperature.

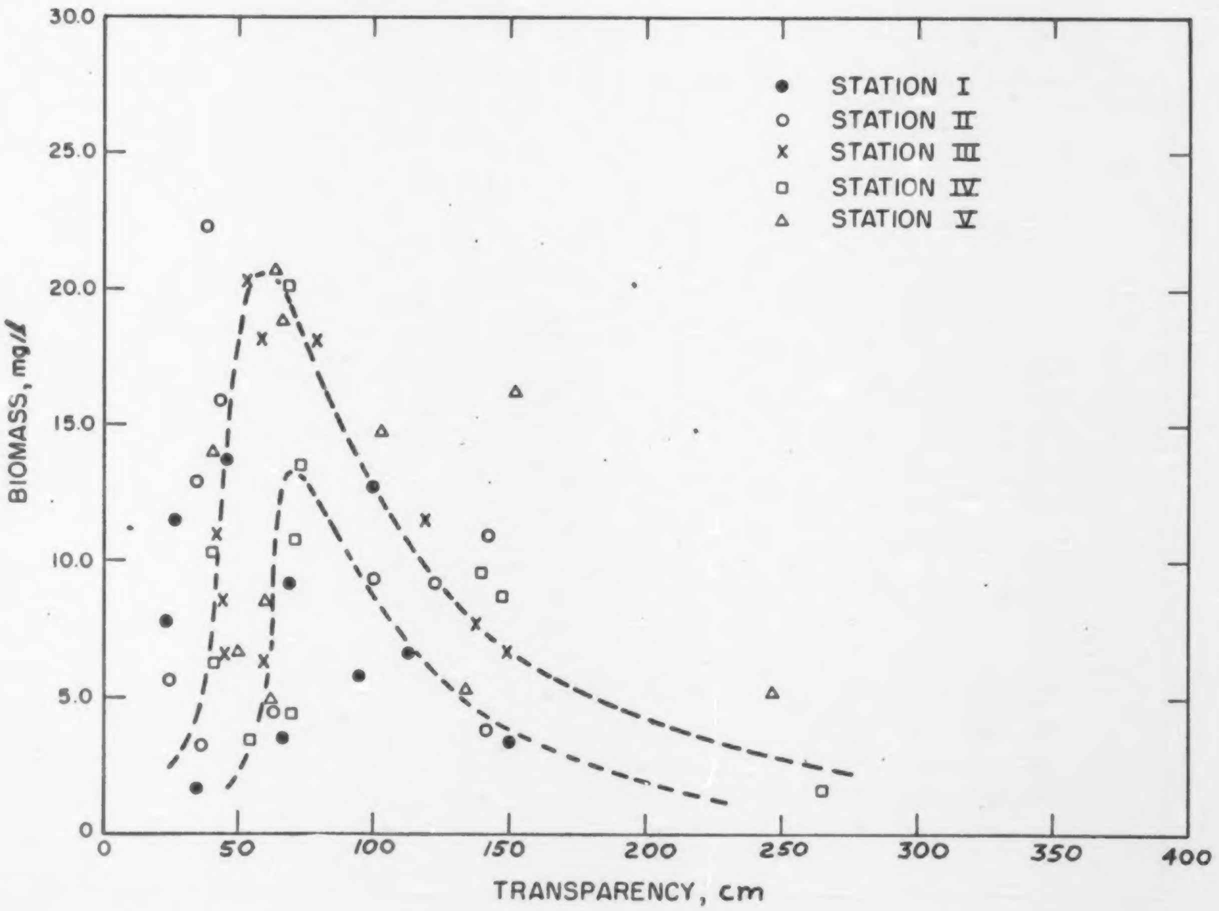


FIGURE 18 Relationship between biomass and transparency of Clear Lake water

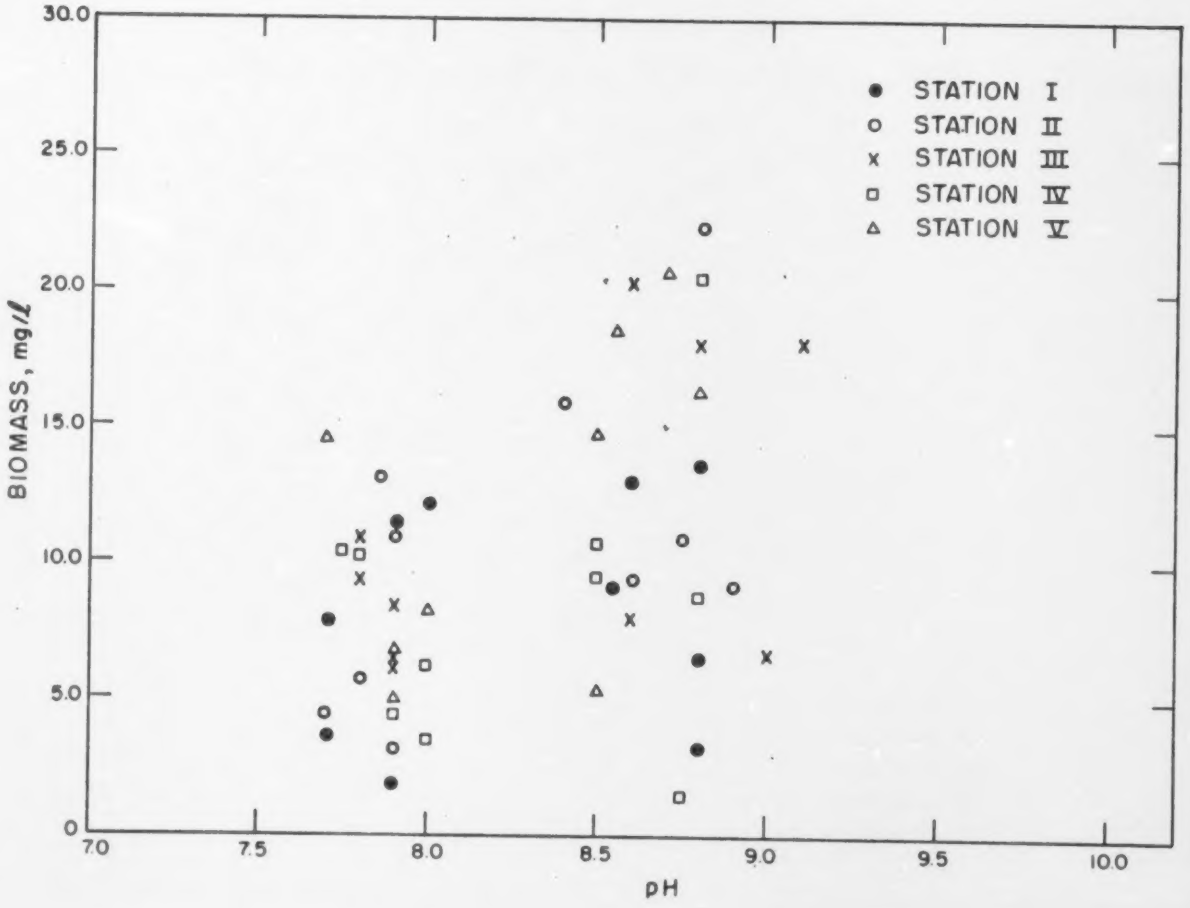


FIGURE 19 Relationship between biomass and pH of Clear Lake water

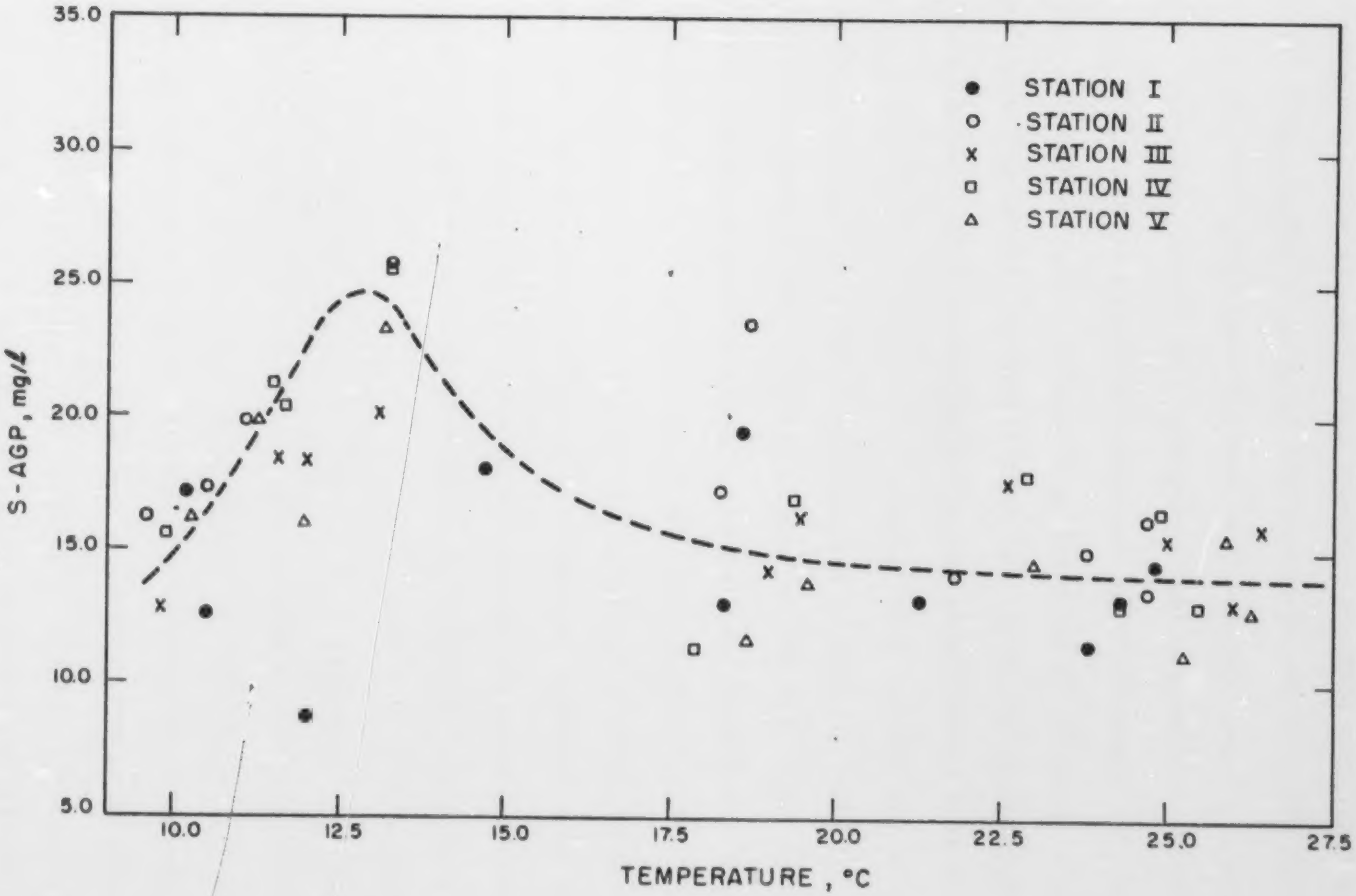


FIGURE 20 Relationship between S-AGP and temperature of Clear Lake water

Presumably low temperature conditions correspond to fall, winter, and spring conditions when new nutrients enter the lake with flood water. Ignoring the small amount of nutrient taken up by Aphanizomenon in the winter, it appears that the lake received about 15 mg/l of SAGP from the runoff source under the low temperature, i.e. winter conditions. The higher SAGP levels found in the scatter of points at about 18°C are believed to be due to an interplay of nutrient releases from the lake bottom, nitrogen fixation, and denitrification. These occur at all times but are more pronounced in the spring and fall. This increment appears to be in the order of 5 to 10 mg/l.

In Figure 21, SAGP is plotted as a function of transparency for all stations. Two zones are apparently involved--one in which transparency and SAGP are directly related and a second in which transparency is inversely related to SAGP. The first relationship is to be expected since water which contains nutrients but not algae would permit greater light penetration than water in which the algae has already grown. The second relationship probably reflects the growth of Aphanizomenon which diminished SAGP as transparency increased. The relationship is however revealed to be quite weak in this case.

Selenastrum AGP and pH

The relationship between SAGP and pH for surface water at all stations is shown in Figure 22. pH increases, of course, occur as a result of photosynthetic activity which in turn would tend to diminish the SAGP. Although the points are greatly scattered by turbidity and other effects, this normal relationship is quite evident in the data. It also appears from the data that the mean change in SAGP due to algae growth alone is about 8 mg/l.

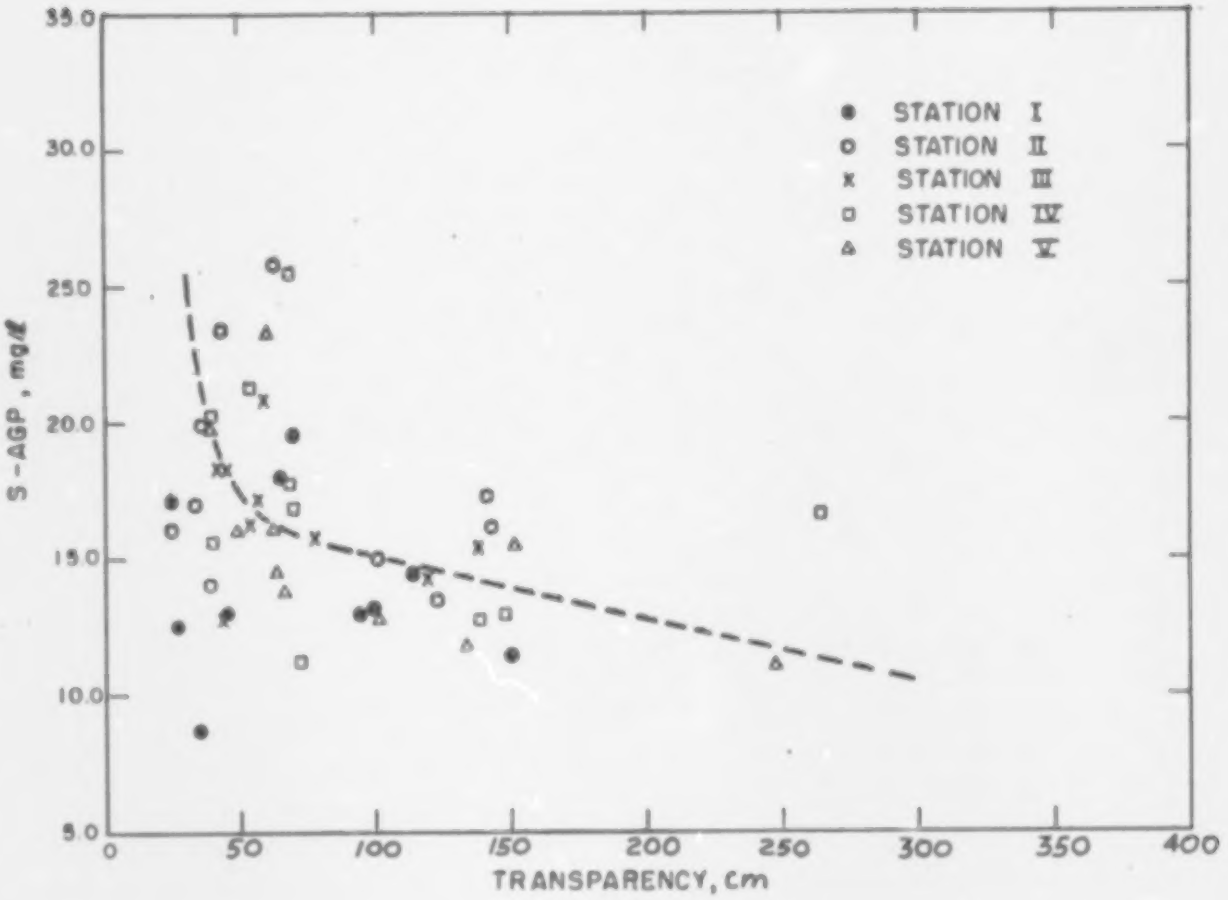


FIGURE 21 Relationship between S-AGP and transparency of Clear Lake water

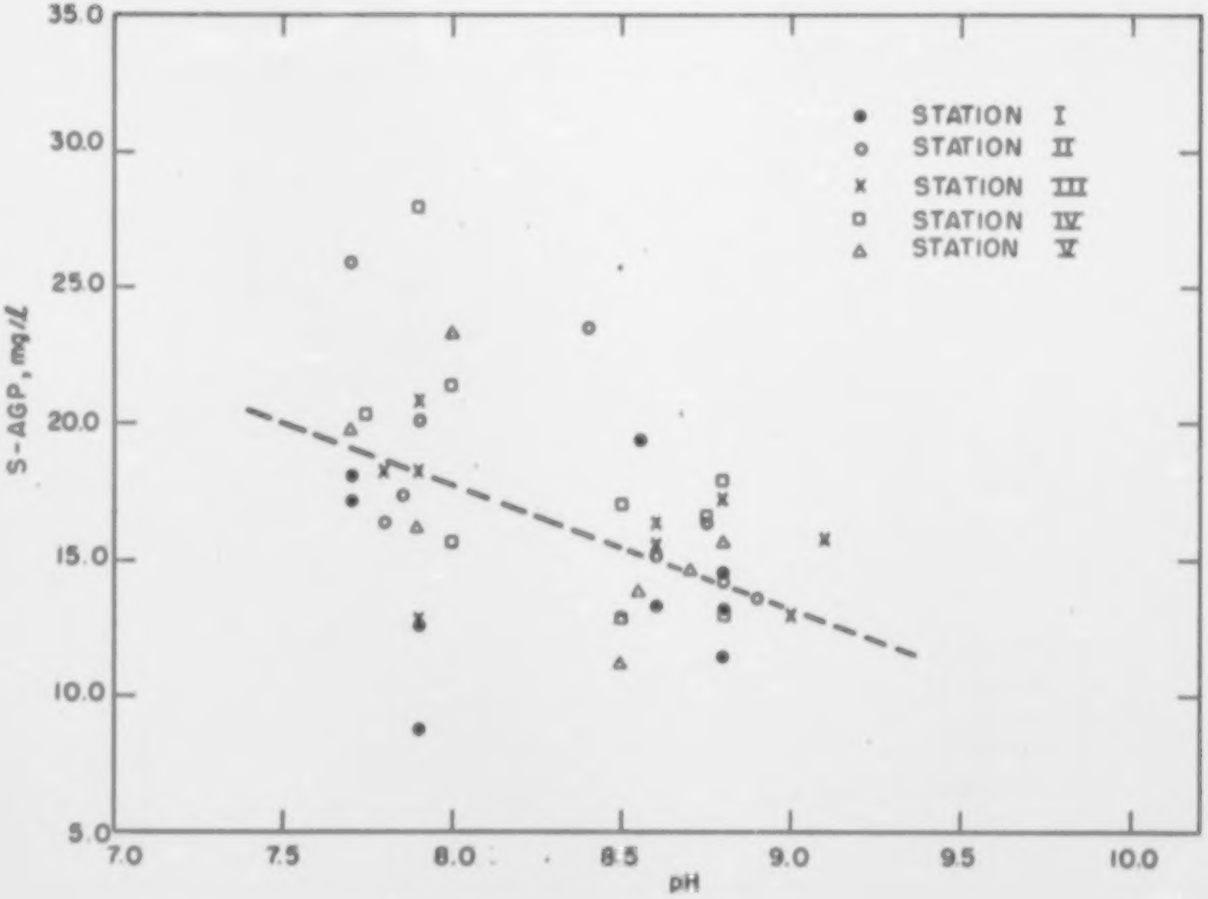


FIGURE 22 Relationship between S-AGP and pH of Clear Lake water

Nutrient Conversion

The data of Table 15 in which SAGP plus biomass, or total available nutrient in terms of algae is tabulated for various dates and stations indicates great variations in the total nutrient base of the lake waters. Values ranging from 3 mg/l in Upper Lake probably reflecting freshly introduced runoff waters, to 70 mg/l in the Oaks Arm of the Lake, probably reflecting either accumulated algae or nutrients upwelling from the lake bottom were found.

Of special interest is the fraction of the total available nutrient actually converted to algae in the lake as a function of the several variables. This is the yield term defined in Equations 2a and 2b.

In figure 23, algae yield percentage, Y, is plotted as a function of total available nutrients, x_p. The plot indicates that the yield tends to increase as a function of available nutrients but that at a total available nutirent level of about 25 mg/l the yield tends to be independent of nutrient level indicating that some factor other than nutrient is often limiting to algal growth within the lake. There is apparently a minimum x_p value of nutrient concentration below which the algae of Clear Lake will not grow. In terms of nitrogen and phosphorus, this would be a level of about 0.5 mg/l of available nitrogen and about 50 μg/l of available phosphorus. These levels are higher than those found for threshold concentrations by Pearson, et al, and may reflect the presence of some factor or substance which inhibits or restricts algal growth when they are present in low concentrations. It should be noted that the data in Figure 23 is for all temperatures observed in all lake stations. Thus the inhibiting factor could be simply temperature or possible a lack of light. It could also be a chemical factor.

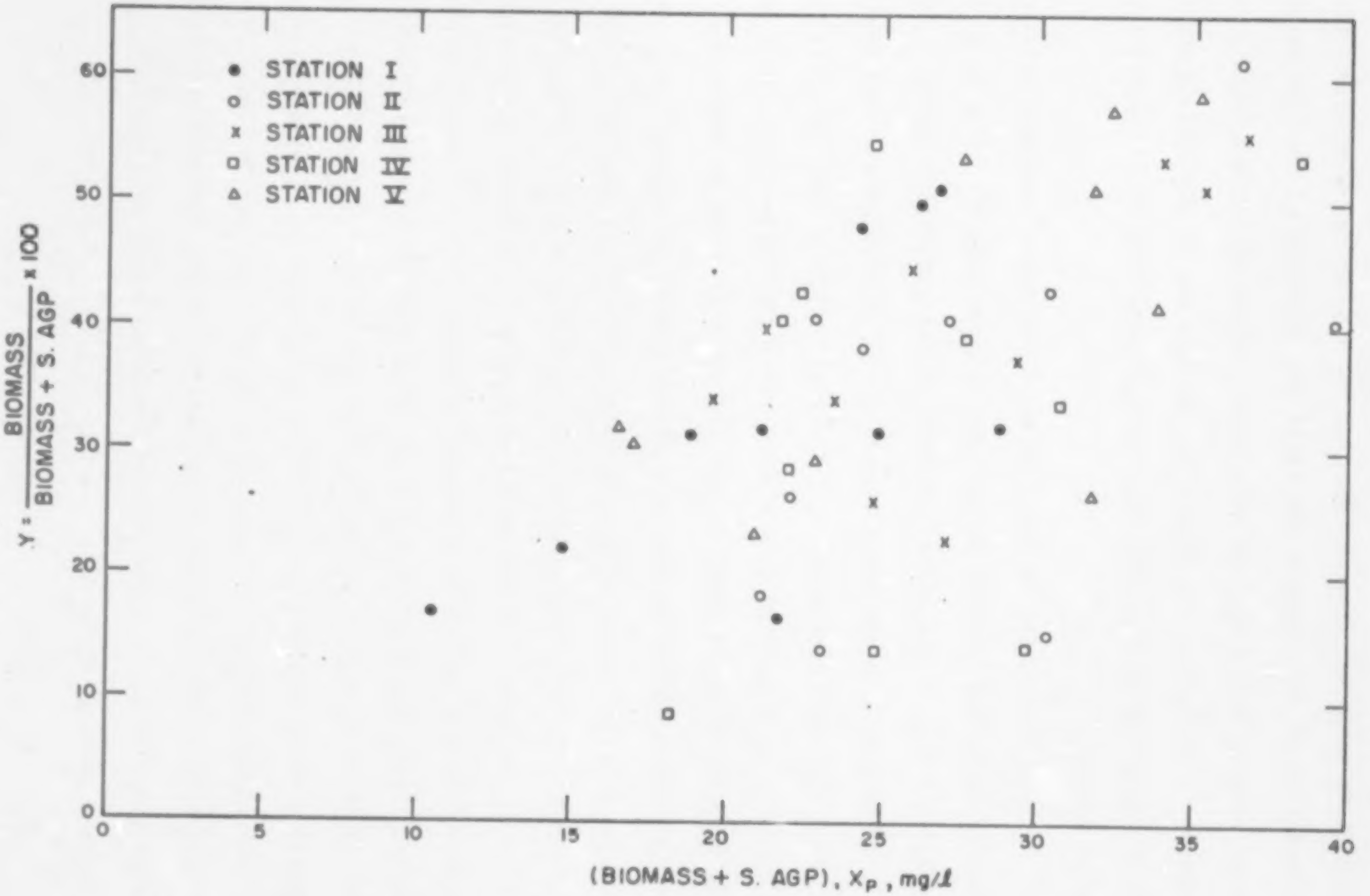


FIGURE 23 Relationship between Y and X_p of Clear Lake water

Nutrient Conversion and Temperature

Values of Y are plotted as a function of temperature in Figure 24. It may be seen in this figure that the lowest Y values occurred at temperatures above the minimum and therefore the possibility of temperature inhibition seems to be at least partially ruled out. As indicated by the dotted line in the figure, highest conversions of total available nutrients are believed to have been attained by Aphanizomenon at about 10-11°C. Above this temperature there was a decline in conversion. The maximum conversion of about 50% was attained at a temperature of about 22°C indicating an optimum for Microcystis and Anabaena at that temperature. At Station V in lower lake, the conversion fraction remained near 55% at the highest temperature but was significantly lower at other stations. Chemical inhibitions and light limitations thus cannot be ruled out but there is no evidence for temperature inhibition at the lowest temperatures.

Nutrient Conversion and Transparency

To test the possibility of light inhibition, yield is plotted as a function of transparency in Figure 25. According to this figure, the lowest yield was attained at the highest transparency. Low yields were also attained at a transparency of 51 cm. According to Equation 1, a 64 cm light penetration would correspond to an algal concentration of 47 mg/l of algae whereas in reality, the concentration was less than 20 mg/l. Thus, clay or silt turbidity was obstructing light penetration in the system and limiting algal growth even at highest yields. Thus, light seems to be most influential as a limiting factor.

Nutrient Conversion and pH

The influence of pH on yield is shown in Figure 26. According to this figure, other factors being equal, pH increases directly with yield. It is interesting to note that the pH vs yield line extrapolates to pH 7 and

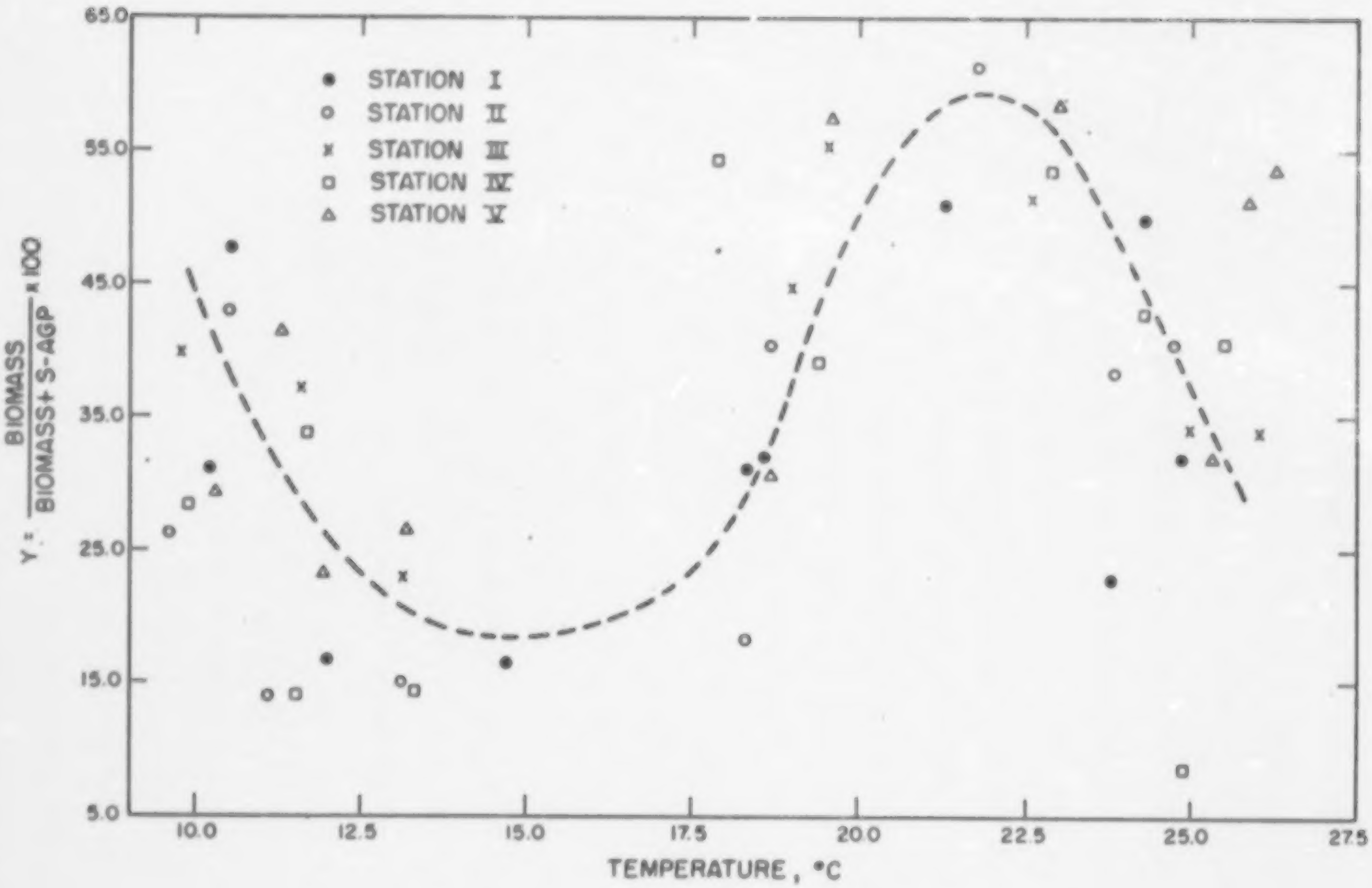


FIGURE 24 Relationship between Y and temperature of Clear Lake water

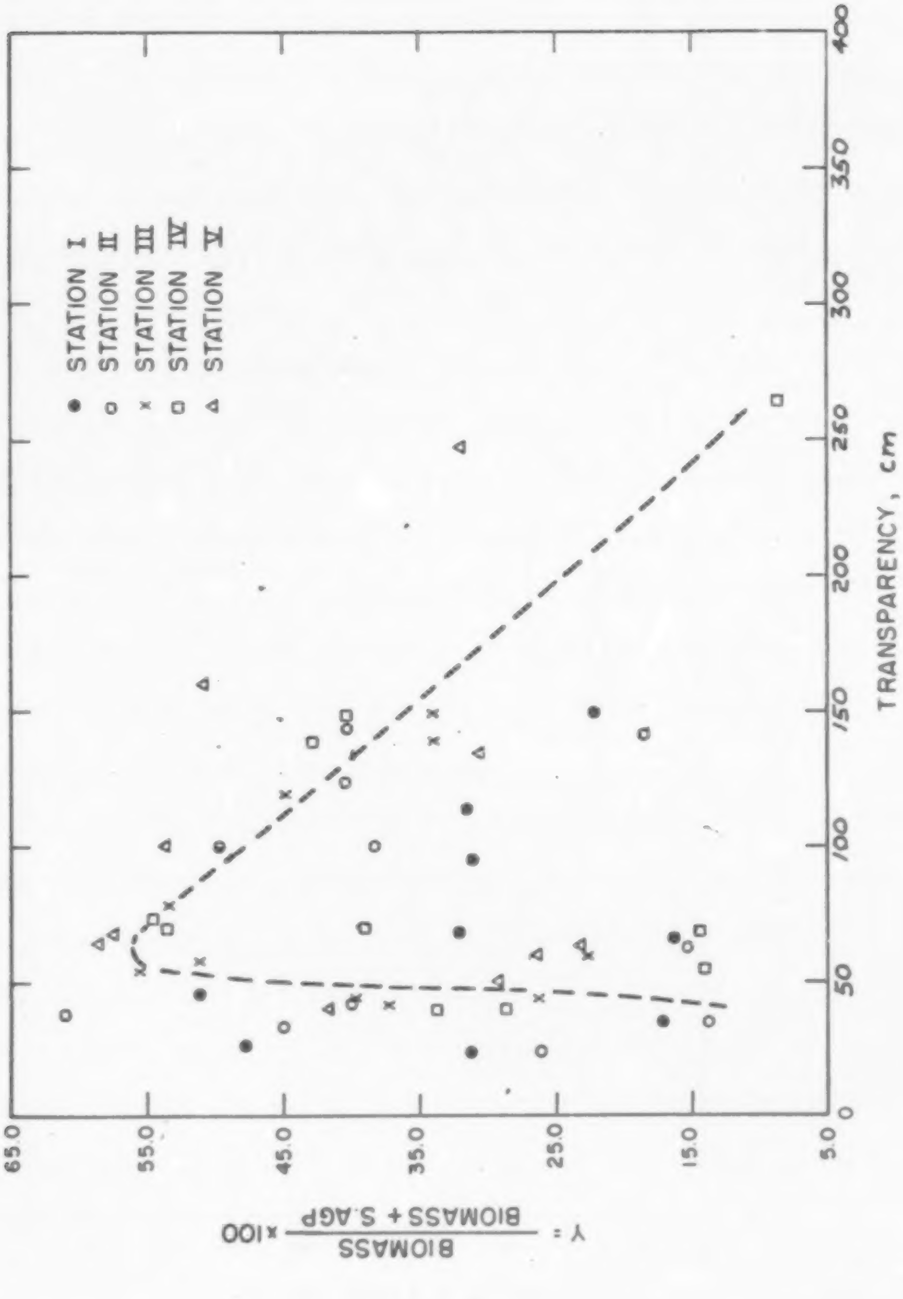


FIGURE 25 Relationship between Y and transparency of Clear Lake water

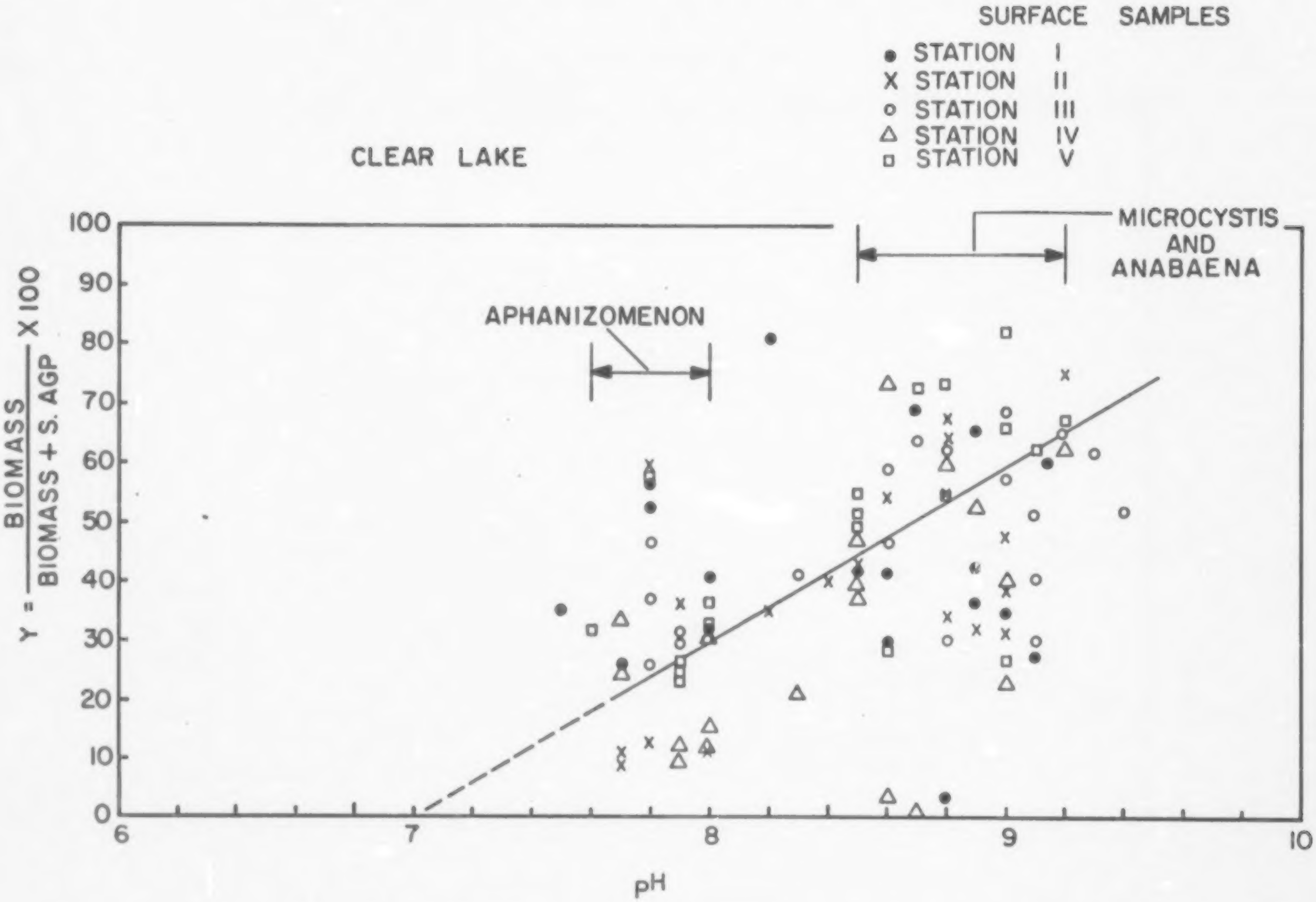


FIGURE 26 Relationship between Y and pH of Clear Lake water

indicates that the yield of algae in Clear Lake would be 0 at pH 7. One interpretation of these data is that Clear Lake algae prefer bicarbonate and free CO_2 as a source of carbon. Another is that low pH conditions are associated with the release of some material, such as a metal ion, that inhibits algal growth. It seems doubtful that the data in Figure 26 is sufficiently accurate to confirm or dispute either hypothesis. Taken with the other data, it does clearly indicate that *Aphanizomenon* grew at a lower pH and had a lower apparent nutrient conversion efficiency than did *Microcystis* and *Anabaena*.

Nutrient Conversion and Alkalinity

The influence of alkalinity on the yield of algae in Clear Lake is shown in Figure 27. It is apparent that the yield is directly proportional to alkalinity but this relationship may be mainly due to seasonal effects. However, other factors being equal, bicarbonate alkalinity apparently had a stimulating effect on SAGP conversion in Clear Lake and high SAGP conversion in the lake caused a proportional decline in alkalinity.

Other Characteristics of Clear Lake Algae

In his studies of growth characteristics of *Aphanizomenon*, Gaonkar concluded that the optimum pH for his Clear Lake species was about pH 7.8. The optimum pH for *Microcystis* and *Anabaena* appears to be about pH 9.0.

Other growth characteristics of *Aphanizomenon*, Clear Lake species as determined and set forth by Gaonkar are as indicated in Table 18.

Gaonkar also in the course of his research developed a basic medium for *Aphanizomenon* (Clear Lake species) growth which is shown in Table 19.

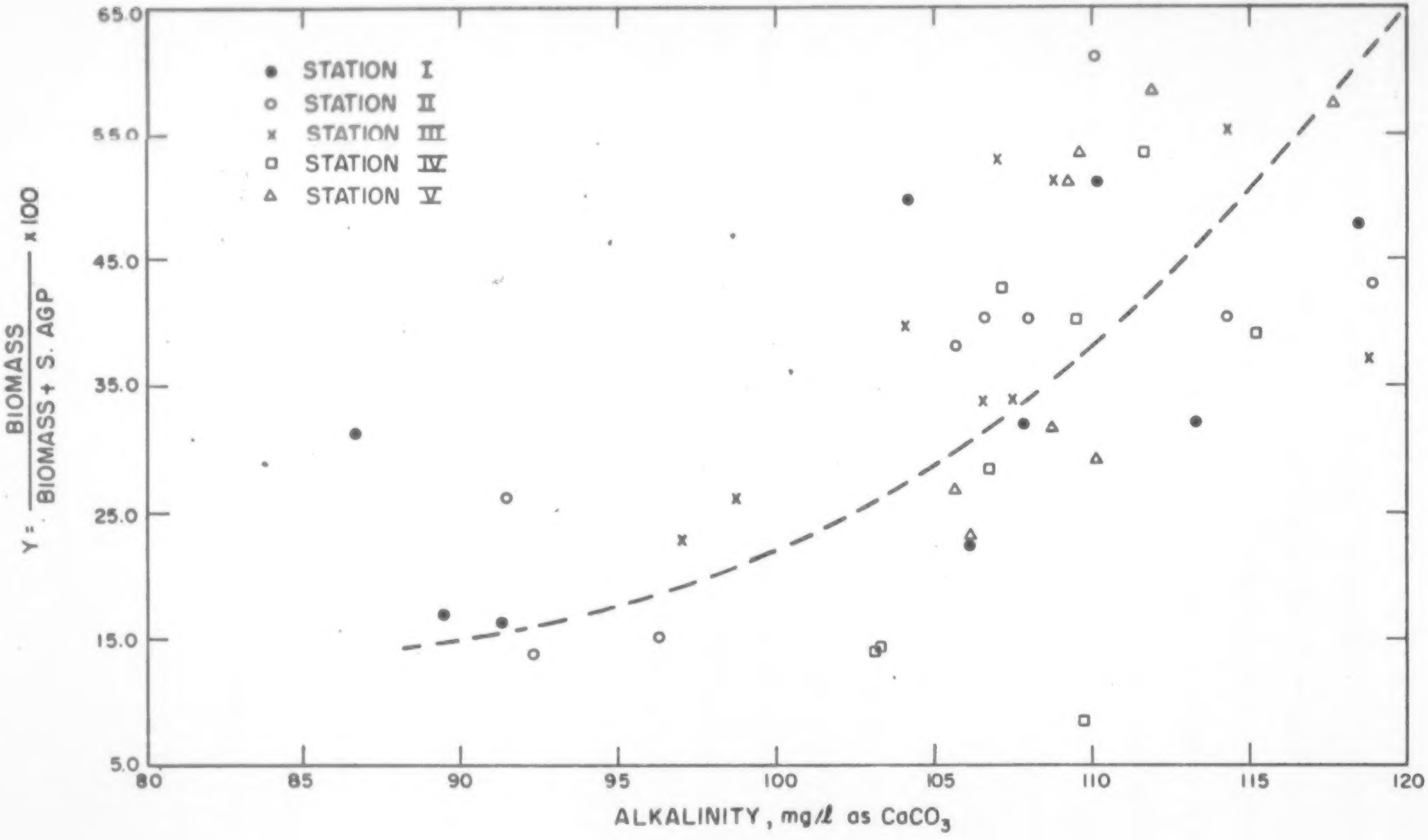


FIGURE 27 Relationship between Y and alkalinity of Clear Lake water

TABLE 18

SUMMARY OF OPTIMUM ENVIRONMENTAL AND NUTRITIONAL REQUIREMENTS OF APHANIZOMENON (CLEAR LAKE SP.)

Temperature	18-24°C
Light Intensity	100-150 Ft-C
pH	7.8
HCO_3	85.4 mg/l
NO_3-N	4.0 mg/l
PO_4-P	0.4 mg/l
SO_4-S	0.5 mg/l
Fe	0.5 mg/l
Ca	20.0 mg/l
Mg[a]	0.25 mg/l
Na	30-60 mg/l
K	0.5 mg/l
Co	3.0 μg/l
Na_2-EDTA	7.44 mg/l (not optimum)
Trace elements[b]	Not required in Clear Lake Water

[a] Requirement not firmly established

[b] Extremely small if required (less than 1 μg/l)

TABLE 19

GOANKAR'S BASIC INORGANIC MEDIUM (GIM) FOR THE GROWTH OF APHANIZOMENON (CLEAR LAKE SP.)

Salt	Conc mg/l	Concentration of Elements& Ions (mg/l)		
$NaNO_3$	22.00	5.96 Na	3.62N	16.00 NO_3
K_2HPO_4	5.60	2.52 K	0.995 P	3.05 PO_4
Na_2HPO_4	7.50	2.43 Na	1.63 P	5.01 PO_4
$MgCl_2 \cdot 6H_2O$	92.00	11.00 Mg	32.00 Cl	--
$MgSO_4 \cdot 7H_2O$	50.70	5.00 Mg	6.6 S	19.7 SO_4
$CaCL_2 \cdot 2H_2O$	88.00	24.00 Ca	42.5 Cl	--
$NaHCO_3$	117.60	32.20 Na	85.4 HCO_3	70 mg/l Alk as$CaCO_3$
Ferric Citrate	0.75	0.14 Fe	--	--
Citric Acid	0.75	--	--	--
H_3BO_3	2.85	0.5 B mg/l	2.72BO_3 mg/l	--
$MnCl_2 \cdot 4H_2O$	21.7 μg/l	6.0 Mn μg/l	7.75 Cl μg/l	--
$ZnCl_2$	83.50 μg/l	40.0 Zn μg/l	43.5 Cl μg/l	--
$CoCl_2 \cdot 6H_2O$	12.10 μg/l	3.0 Co μg/l	3.61 Cl μg/l	--
$CuCl_2 \cdot 2H_2O$	2.70 μg/l	1.08 Cu μg/l	1.12 Cl μg/l	--
$Na_2 \cdot MoO_4 \cdot 2H_2O$	24.20 μg/l	4.60 Na μg/l	9.6 Mo μg/l	16.0 MoO_4 μg/l
$Na_2.EDTA.2H_2O$	7.44 mg/l	0.92 Na mg/l	0.56 N mg/l	--
Gaonkar's Micronutrient Solution for the Growth of Aphanizomenon C.L. sp.)				
	Conc μg/l	Concentration of Elements & Ions (μg/l)		
$AlCl_3$	0.50 mg/l	0.11 Al mg/l	0.39 Cl mg/l	--
$LiCl_2$	30.0	4.92 Li	25.08 Cl	--
TiO_2	5.0	3.0 Ti	--	--
KI	10.0	0.8 K	2.55 I	--
KBr	15.0	2.45 K	5.05 Br	--
V_2O_5	5.0	3.3 V	--	--
$SnCL_2 \cdot 2H_2O$	3.0	1.578 Sn	0.945 Cl	--
$NiSO_4 \cdot 6H_2O$	10.0	2.25 Ni	1.22 S	3.65 SO_4
$Na_2SiO_3 \cdot 9H_2O$	60.0	9.7 Na	5.9 Si	16.1 SiO_3
$Cd(NO_3)_2 \cdot 4H_2O$	10.0	3.65 Cd	0.91 N	4.03 NO_3
$Cr(NO_3)_2 \cdot 9H_2O$	15.0	1.95 Cr	1.57 N	6.97 NO_3

P = 2.625 mg/l; PO_4 = 8.06 mg/l; N - 3.62 mg/l (No EDTA N); NO_3 = 16.0 mg/
S = 6.6 mg/l; SO_4 = 19.7 mg/l; K - 2.52 mg/l; Na ≅ 41.5 mg/l
Ca = 24.0 mg/l; Mg = 16.0 mg/l; Fe = 0.14 mg/l
B = 500 μg/l; Mn = 6.0 ug/l; Zn = 40.0 μg/l; Co = 3.0 μg/l
Cu = 1.08 μg/l; Mo = 9.6 μg/l

A diagram of Clear Lake *Aphanizomenon* is shown in Figure 28. In the diagram, the following terminology is used:

Trichome: Single Filament
Vegetative Cell: Individual units of the trichome
Heterocyst: Specialized cell of a trichome having a length and width characteristically different from those of vegetative cells.
Colony: A bundle of several hundred trichomes.
Clump: An aggregation of colonies.

Physical size is particularly important with respect to screening and removal of floating algae. The *Aphanizomenon* found in Clear Lake and shown in Figure 28 have the following dimensions for the indicated structures:

Vegetative Cells: Length = 8.5μ - 13.5μ ; Dia. - 5μ - 7μ.
Colony: 1 mm to 2 mm or more.
Heterocyst: Length - 10μ - 13.5μ ; Dia. - 6μ - 7μ.
Akinete: Length - 47μ - 60μ ; Dia. -7μ - 8μ.

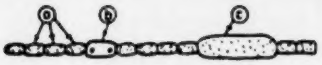
Sources of nutrients in Clear Lake

In Clear Lake two sources of nutrients other than nitrogen fixation are considered to be of major importance. These are inflow and recycle from the lake bottom. Gaonkar studied inflow samples and bottom samples from the standpoint of organic content and AGP. He found the average organic content of bottom muds to be as summarized in Table 20.

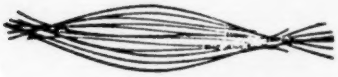
TABLE 20

Arithmetic Mean and Range of % Total Volatile Solids in the Bottom Mud of Clear Lake (Dec 1969 to Oct 1970)

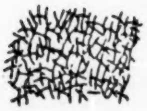
Stations				
I	II	III	IV	V
14.20 12.45-13.88	17.60 14.95-20.00	17.70 9.40-28.70	20.00 18.20-22.90	13.10 3.62-21.70



A. TRICHOME
(a) VEGETATIVE CELLS
(b) HETEROCYST
(c) AKINETE



B. COLONY



C. CLUMP

FIGURE 28- NOMENCLATURE AND FORMS OF *APHANIZOMENON*

He then made extracts of the mud and determined the algal growth potential of the extracts to be about 1.1 mg of SAGP per gram of mud. From this, one may calculate that the nutrients in the top centimeter of Clear Lake muds could support the growth of about 3,000 metric tons of algae or about 2 mg/l. The mean biomass in the lake on the other hand, is on the order of 10 mg/l or about 14,000 metric tons.

It therefore seems likely that nutrients entering the lake from its tributaries contribute substantially to the initial SAGP. Gaonkar's studies of the SAGP of the various creeks entering the lake gave the results shown in Table 21.

TABLE 21

S-AGP OF LAKE COUNTY CREEK SAMPLES

Name of Creek Collection Date	% Sample	AGP mg/l
Adobe Creek	99	14.60
12/15/69	50	15.90
Siegler Creek	99	13.40
12/15/69	50	17.70
Middle Creek	99	13.00
12/19/69	50	14.30
Scotts Creek	99	11.05
12/19/69	50	11.10
Manning Creek	99	12.58
12/19/69	50	15.50
	10	15.70
Kelsey Creek	99	15.30
12/19/69	50	15.70
	10	15.70

As indicated in Table 21, no stream had SAGP levels less than 11 mg/l and Siegler Creek had an SAGP of 17 mg/l. If we assume a mean inlet AGP of 12 mg/l and assume that 1/3 of the lake volume is replaced each year the inlet SAGP could be 5,640 metric tons. According to Gaonkar's data for total available nutrients, the mean level averages 19.3 mg/1 or 27,200 metric tons. The inlet SAGP and recycled SAGP would total 8,640 metric tons annually whereas the algal biomass averages about 10,000 metric tons. Thus, at least 2,000 metric tons of SAGP may be contributed by nitrogen fixation. This is equivalent to 200 tons of nitrogen; somewhat less than the approximated 500 metric tons estimated by Horne(4), but of the same order of magnitude. If the data in both cases were correct, denitrification could amount to some 300 metric tons per year.

SCUM FORMATION MODEL

Based upon the foregoing studies of DWR and Gaonkar, as interpreted herein, a phenomenological model of microalgae scum formation and nutrient recycle can be drawn up which appears to best fit the currently available facts. The model consists of a series of somewhat irregularly recurring processes and events which may be described in the following steps:

1. Thermal stratification of a body of water due to high sunlight energy input and lack of mixing. This results in formation of a warm oxic upper zone and a somewhat cooler and at least partially anoxic lower zone. The two zones are separated by a thermal gradient or "Thermocline".

2. A period of wind mixing of intensity sufficient to cause deterioration of the thermocline, overturn of the waters and mechanical transport of soluble nutrients from the bottom of the lake into the surface and translocation of insoluble materials toward the lake bottom.

3. An ensuing relatively wind-free period during which a stable thermocline becomes re-established as the layer of water above the thermocline continues to be warmed by sunlight.

4. Logarithmic multiplication of viable algae in the waters of the warmer, re-enriched volume above the thermocline.

5. Intensified thermal stratification of water due to absorption and conversion of light energy to heat by turbidity and by algae within the volume above the thermocline.

6. Assimilation of nutrients by photosynthesizing algae and depletion of some critical nutrient "s" in the surface water through its almost complete assimilation by algae or bacteria or through its precipitation due to the increase in pH normally accompanying photosynthesis.

7. Inhibition of algal multiplication due to lack of nutrient "s".

8. Increasing tendency of nutrient deficient algae to rise to the surface or decreasing ability of nutrient deficient algae to remain submerged due either to physiological impairment or to their stage of growth (age).

9. Continued but imparied or incomplete photosynthetic activity of algae in the nutrient depleted surface waters with assimilation of carbon and possibly nitrogen but with algae production and release of soluble organic, "shunt" products into the thermally stratified layer of surface water.

10. Decrease in surface tension of water due to the presence of algae or algal products (remains to be proved).

11. Horizontal concentration of algae into "slicks" due to decreased surface tension in areas where accumulation begins (remains to be proved).

12. Continued accumulation of algae, shunt products of algal metabolism, precipitates, and detritus in certain areas due to changes in surface tension together with increase in pH (remains to be proved).

13. Growth of fungi, bacteria and photo-organotrophic algae in slicks due to presence of soluble organic matter.

14. Wind movement and concentration of algal masses or "slicks" along beaches and in cul de sacs of the body of water.

15. Cessation of photosynthetic activity by algae and death and disruption of algae due to one or a number of the following: (a) excess light with lack of nutrients, (b) deprivation from light and nutrients, (c) heating, (d) drying, (e) autolysis, (f) attack by predators, (g) attack by fungi , bacteria, or viruses, (h) toxicity.

16. Accelerated decomposition of dead or dying algae and their extracellular products by facultative heterotropic bacteria and fungi. Such decomposition may be accompanied by oxygen depletion and anoxic conditions in surrounding waters.

17. Development of anaerobic decomposition of accumulated organic matter with formation and release of organic acids and other complex compounds containing carbon, nitrogen, phosphorus and trace nutrients.

18. Decomposition and release of nutrients into solution due to their increased solubility in acid medium.

19. Mechanical transport of soluble substances into surrounding waters by gas bubbles which emerge from the decomposition zone and rise through the water providing vertical mixing. Wind overturn and possibly boat mixing also contribute to mixing and transport of soluble substances.

Inasmuch as the above phenomena occur in cyclic fashion, the fact that they are numbered does not imply a rigid sequence of events. Numbers are used herein mainly for reference purposes. The numbers however, do reflect the sequence in which the processes are believed most likely to occur.

SCUM PREVENTION AND CONTROL

Because the individual phenomenon are apparently to some extent cyclic in nature, an interruption of one key portion of the cycle could interfere with the entire cycle. Each phenomenon has been considered with respect to the extent to which it may be influenced by natural phenomena and man-made procedures. Dilution, grazing of algae with fish, mixing of the body of water to obliterate the thermocline and attendant nutrient release problems, retention of nutrients in upstream reservoirs, dredging to remove bottom nutrients and direct removal of algal scums are among the schemes which have been seriously considered for improvement of Clear Lake. Direct removal is of course attractive because all nutrients taken up in this fashion are subject to complete and permanent removal from the lake. The remainder of the report is devoted to consideration of methodology and experiments on direct algae removal.

SECTION IV

ALGAL SCUM REMOVAL

BENEFITS OF SCUM REMOVAL

Direct removal of concentrated surface algal scums will result in at least three distinct benefits to a eutrophic body of water. These are:

1. Immediate removal of the scums which are objectionable to the senses and hence detrimental to property value and recreational use.

2. Permanent removal from the lake of those nutrients incorporated in or adhering to those algal cells removed.

3. Prevention of sedimentation of the algal scums and thus interruption of acid fermentation which is believed to be one of the major mechanisms for release of ammonium and soluble phosphate from organic and inorganic bottom deposits.

UNIT PROCESSES FOR SCUM REMOVAL

From past experience with algal separation (1) the investigation was initiated on the premises that physical removal of algae from natural bodies of water should involve at least three major steps:

1. Capture of algae from the water surface with a minimum amount of vehicle water;

2. Concentration of the algae by removing the vehicle water with return of the vehicle water to the lake; and

3. Preparation of the algae for disposal.

CAPTURE AND PICKUP OF FLOATING ALGAE

The slippery nature of the blue green algae scum, its hydrophilic properties (i.e. a tendency to stay in water), its lack of structural or "bridging" strength, and the limp characteristics of filaments usually found in scum renders continuous large scale capture and pickup of Aphanizomenon and other micro-algae a difficult step.

A large number of pickup devices have been developed for removal of oil from the surface of water and one might presume that the apparatus would be the same for removing algal scums as for removing oil scums. Unfortunately this is not true. Oil scum removal systems are generally based on the concept that oil tends to separate from water because it has hydrophobic properties. For example, rotating disks normal to the water surface will lift a film of oil from water because the oil adheres to the disk surfaces more readily than it remains in the water. The oil lifted up by the disks can then be "doctored" or "squeegeed" from the disk surface and thence removed in a continuous process. Also, certain types of sponges or sponge material will absorb oil or grease in water and as the spongy material is removed from water, the oil adheres to it and is removed also. With the exception of algal scums that may be entirely dead, or co-mingled with oil or grease, surface algal scums unlike oil and grease, are generally repelled by surfaces newly intruding into a water-algae mixture. The result is that disks or sponge pickup as used for oil are virtually useless for a continuous algae pickup process.

A third type of oil pickup device is a simple floating skimmer. This unit was developed and placed on the market by ACME Products Corp. of Tulsa, Oklahoma in 1970. The unit essentially is a skimming trough supported by a float. The trough is emptied by a 3 -h.p. motorized pump. The skimming trough is attached to the float so that the intake lip position can be adjusted with respect to the water surface. This feature is best understood by examining the schematic cross-section of the unit given in Figure 29.

One of the units shown in Figure 29 was purchased so that algae could be obtained for experimental purposes and for testing secondary concentration devices. However, it was recognized at the outset that such a device was only of interim value in the project. The fundamental problem to be solved in the project was development of a versatile cost effective pickup device, hence, the floating skimmer pump in Figure 29 was regarded only as a temporary unit to be replaced by a unit especially designed for algae rather than oil.

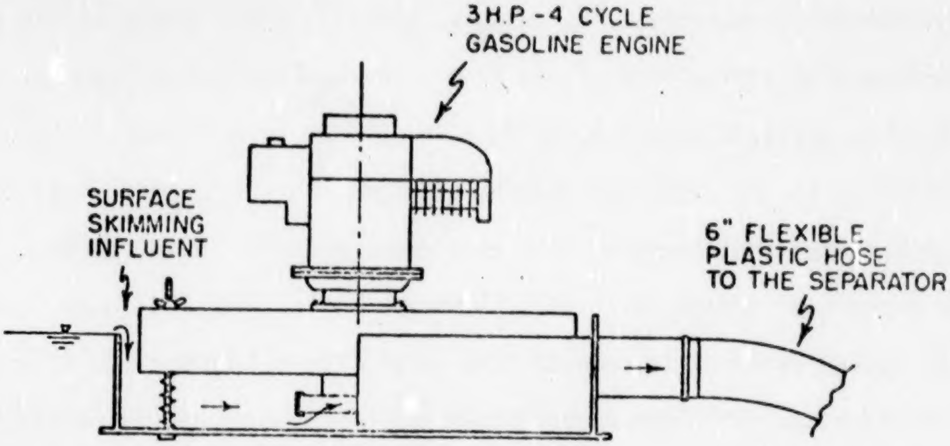

3H.P.-4 CYCLE GASOLINE ENGINE
SURFACE SKIMMING INFLUENT
6" FLEXIBLE PLASTIC HOSE TO THE SEPARATOR

FIGURE 29 Floating skimmer Pump

SECONDARY CONCENTRATION

While the interim pickup unit was in use, considerable thought was given to secondary concentration devices to be operated in series with the primary pickup unit. Various sorts of continuous and solid bowl centrifuges, linear centrifugal and cyclonic separation devices, as well as settling and screening devices were considered in detail for their potential concentration effects. The findings of this study were reviewed in detail in the 5th progress report(8). The conclusion of that report was that the screening or straining principal was most feasible for secondary concentration of micro-algae. The rationale for this was as follows:

1. Straining is a low unit cost process for small particle separation.

2. A 250 mesh strainer will easily remove filamentous algal clumps and even individual filaments of *Aphanizomenon*, *Anabaena* and *Microcystis*.

3. Concentration factors of 10 or 20 to 1 can be easily attained in strainers.

4. The concentrated material from a microstrainer is sufficiently liquid to be pumped and yet because of its reduced volume can be further concentrated by settling or centrifugation at relatively low costs.

After a review of many screening techniques, two screen types selected for further study, namely, the microstrainer and the cascade screen type known as "DSM" or "hydrosieve".

Commercial microstrainers are manufactured by a number of companies at this time. Because the use of the microstrainer principle seemed to be highly promising and because a commercial unit would be too heavy and expensive, a portable rotary separator was constructed by the University Field Station shops from available materials and components. A schematic diagram of the unit is shown in Figure 30.

To determine the effectiveness of the "home-made" microstrainer in concentrating algae from Clear Lake water, dry weights of suspended solids in influent, effluent, and in the concentrate were used as parameters. Results of these experiments are shown in Table 22. As is shown in the table, concentration factors of about 10 to 1 and approximately 50% solids removal were obtained. However, recognizing that the feed solids were perhaps only 50% algae, higher removal values and higher

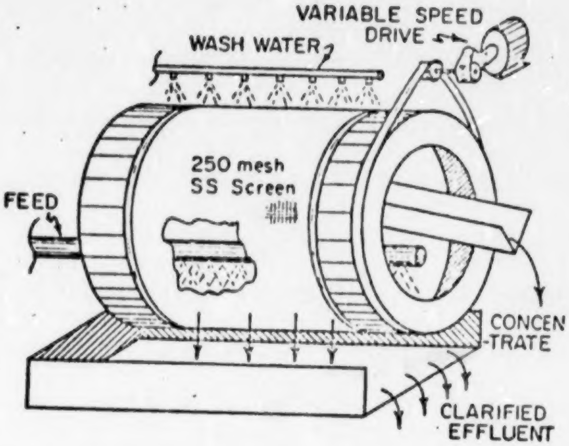

VARIABLE SPEED DRIVE
WASH WATER
250 mesh SS Screen
FEED
CONCEN -TRATE
CLARIFIED EFFLUENT

FIGURE 30 Portable rotary strainer

TABLE 22 PRELIMINARY RESULTS WITH SABANAS PORTABLE ROTARY STRAINER II

Date	Screen Size		Drum Velocity m-min^{-1}	Inf. Rate liters-sec^{-1}	Dry Weight Conc. mg/l^{-1} (1)			Percent Solids Removal	Conc. Factor X_m/X	$\frac{X_m}{C_p}$(2)
	Meshes in	μ			Inf	Eff	Conc.			
Aug 26	250	100μ	30	.28	43	29.3	504	32	11.8	25.2
"	"	"	"	.51	42	27.8	105	34	2.5	5.2
"	"	"	"	.68	41	21.6	120	47	2.8	6.0
"	"	"	"	.84	37	20.1	178	46	4.8	8.9
Oct 14	200	125μ	"	.15	136	68.0	484	50	3.5	24.1
"	"	"	"	.18	113	69.8	322	38	2.8	16.1
"	"	"	"	.37	120	60.2	343	50	2.8	17.1
"	"	"	"	.18	83	66.8	357	20	4.2	17.8
Oct 20	"	125μ	51	.34	99.3	40.5	104	18.7	2.1	5.2
"	"	"	43	"	50.2	39.3	103	21.7	2.1	5.1
"	"	"	36	"	52.0	38.5	137	26.0	2.7	6.9
"	"	"	28	"	50.6	40.3	132	20.4	2.6	6.6
"	"	"	20	"	49.3	39.7	171	19.5	3.5	8.6

(1) Based on samples filtered through Watman G.F.C. glass fiber filters not ashed

(2) Assuming C_p = 20

concentration factors were actually attained than those shown in the table. For example, if an overall concentration factor is computed assuming an input value of 20 mg/l, concentration factors above 25 and removals approaching 90% are obtained. It should also be noted that influent concentrations were extremely low. Had feed concentrations approached those actually observed at the lake surface in critical areas requiring straining, much higher performance would have been obtained. The low algal concentrations in the feed in Table 22 resulted from the fact that the floating skimmer pickup unit shown in Figure 29 functioned very poorly, drawing algae only from the immediate vicinity of the unit. As soon as the algae in the immediate vicinity were depleted, the unit had to be moved and movement disturbed the algal scum to an extent that would be impermissible in a practical operational system.

Cascade Screens: Preliminary work with a Dorr Oliver DSM screen showed that this unit was also too expensive and cumbersome for our small scale experiments although it would be quite practical for a larger system. Fortunately, a small portable experimental "hydrosieve" unit having one square foot of screen area and based on the DSM principle was made available to the project free of charge by the manufacturer (Bauer Brass Co.).

Experiments were conducted at Clear Lake using the Hydrosieve in series with the portable skimmer shown in Figure 29. The floating skimmer again functioned inefficiently in skimming the surface algae so that as in the case of the rotary strainer, results obtained were very conservative. Concentration results obtained with the sieve are tabulated in Table 23.

TABLE 23 REMOVAL AND CONCENTRATION WITH A HYDROSIEVE, OCTOBER 9, 1970

Flow Rate $\frac{\text{liters/sec}}{m^2}$	Screen Opening microns	Algae Concentrations dry weight mg/liter			% Solids Removal	Conc. Factor X_m
		Influent mg/1	Effluent mg/1	Concentrate mg/1		
1.2	38	32.0	22.5	145.4	30	4.5
1.8		32.2	18.9	90.0	41	2.8
2.2		57.4	35.7	430.0	38	7.5
2.3	44	62.4	35.4	133.0	43.4	2.1
5.0		33.3	24.9	541.0	25.4	16.3
5.7		30.9	23.3	327.0	21.4	10.6
3.7	55	30.0	22.5	264.0	31.7	8.8
6.8		31.2	27.3	398.0	12.5	12.7
11.0		30.0	28.5	108.0	5.0	3.6
12.3		30.0	26.0	261.0	13.3	8.7

As is evident in Table 23, in spite of the fact that a substantial algal scum was present, due to poor pickup performance the mean feed concentration was only 30 to 60 mg/l total solids, and perhaps 15 to 30 mg/l algae. The difference as determined by later analyses was made up of very fine silt. Corrected for these factors, the percent algae removal could be as high as 80% and the concentration factor 15 to 1 or more in a functional system. Concentration factors and removals attained in the system under varying conditions are presented graphically in Figures 32 and 33. As is evident in Figure 32, percent removal was inversely proportional to flow rate and probably reached 40% for total solids and pernaps as much as 80% for algae. Best removals were attained with 38μ and 44μ screening opening, and when the 55μ opening was used removals were relatively low.

As shown in Figure 33, highest concentration factors were attained with the 44μ and 55μ screen openings at flow rates of 4 to 5 liters per square meter per second. Had an adequate pickup system been available, it appears that both the hydrosieve and the rotary screen would give an overall concentration factor of at least 20 to 1 with slurry concentrations up to 5 grams per liter. Thus, two systems are apparently available for secondary concentration of algal scums.

A functional pickup superior to the unit depicted in Figure 29 is essential to any practical removal system.

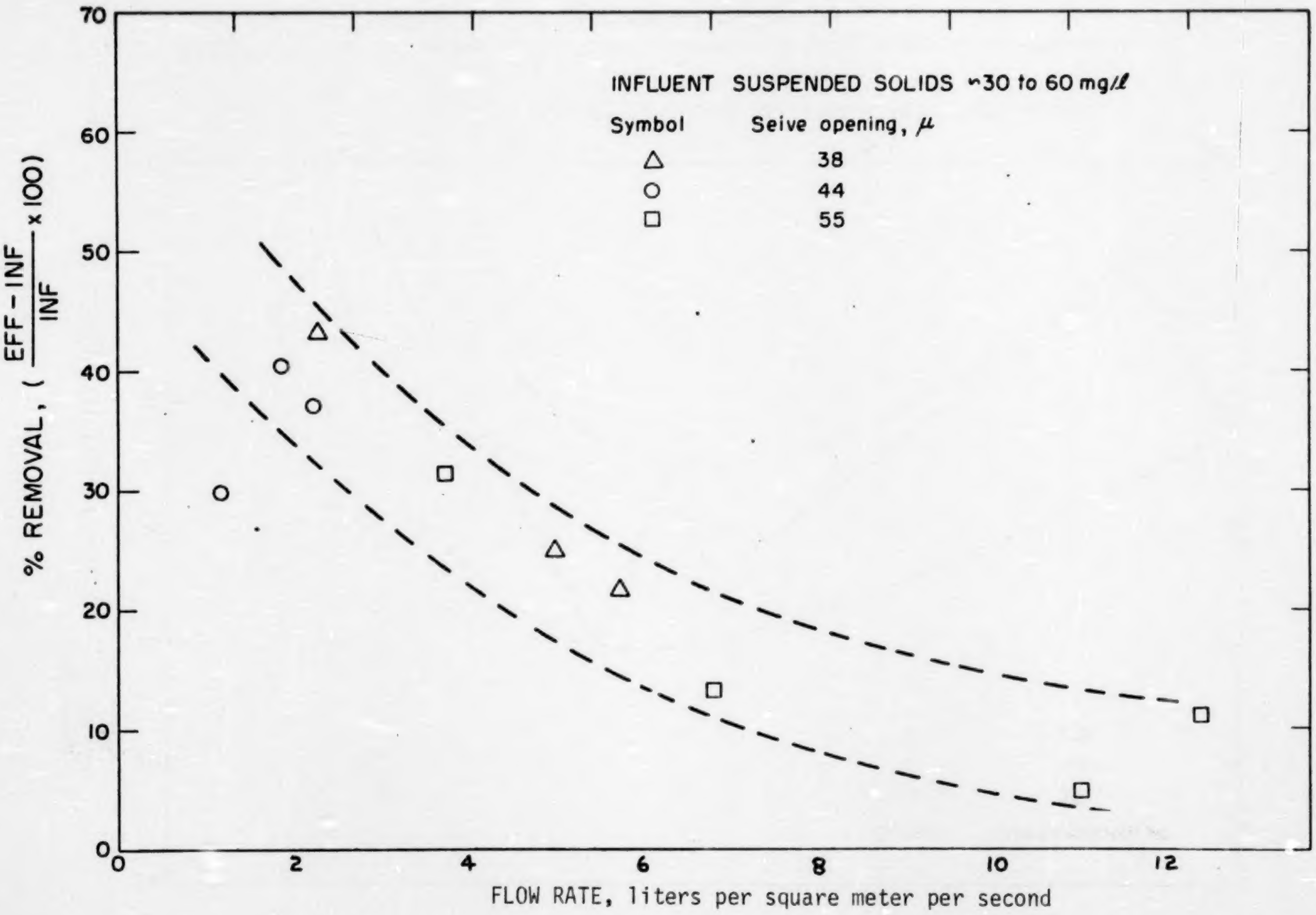


FIGURE 32 Removal of suspended Aphanizomenon by a hydrosieve as a function of flow rate and sieve opening

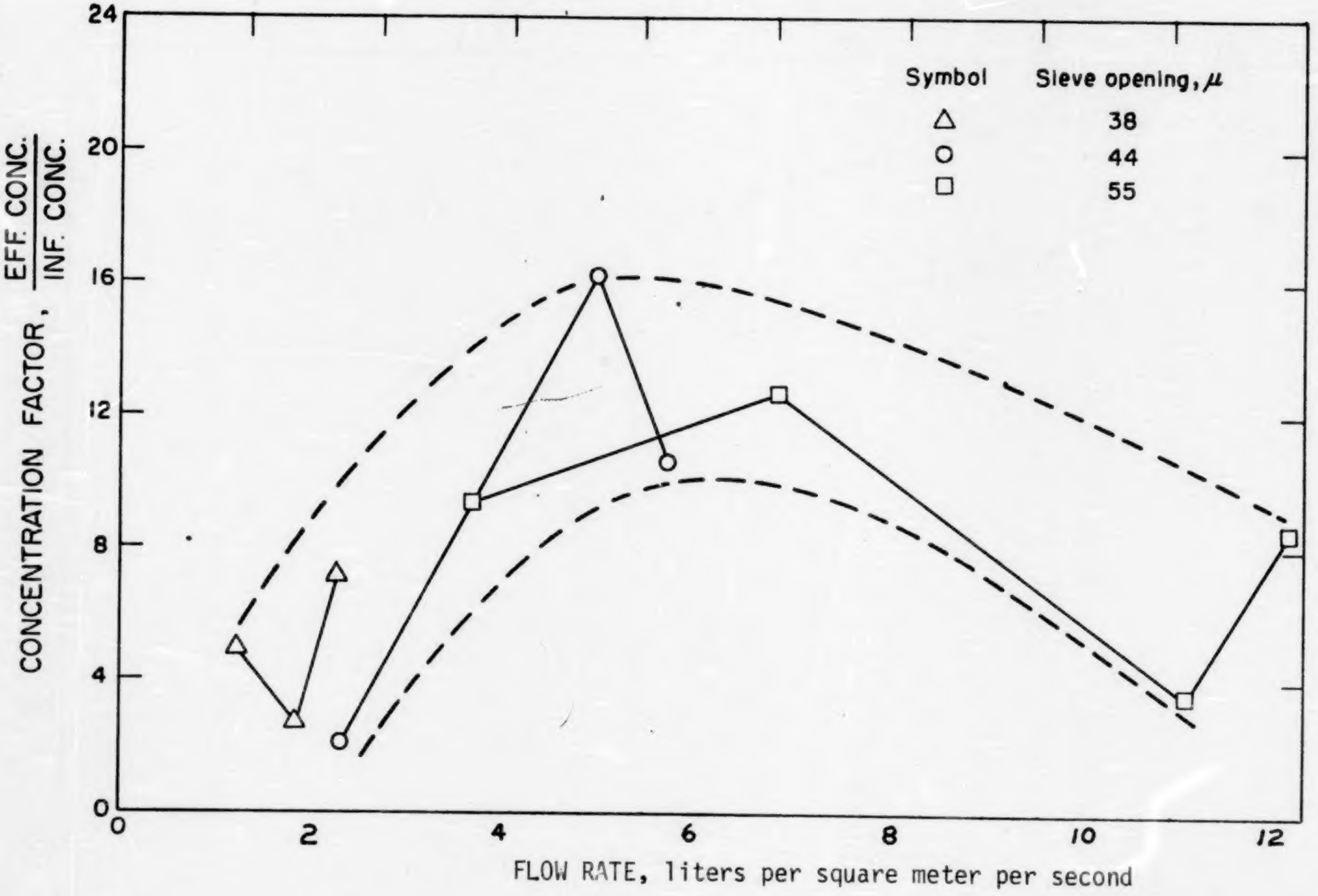


FIGURE 33 Concentration factors for Suspended Aphanizomenon by a hydrosieve as a function of flow rate and sieve opening

COMBINED PICKUP AND SECONDARY CONCENTRATION

One possible system configuration which was suggested to combine the floating skimmer in Figure 29 with the portable microstrainer from Figure 30 is shown schematically in Figure 34. This was essentially the system utilized in obtaining the experimental data reported in Tables 22 and 23 and consequently this is the first algae pickup system utilized.

As portrayed in Figure 34, the system involved a moveable boom supporting the floating skimmer and using a barge to support the boom and scanning device as well as the strainer. Unfortunately there are two major problems with the floating skimmer of this system. As noted above, the algae are not drawn to the skimmer very well since approach velocities a few feet from the skimmer are very low and the flow of algae to the skimmer itself creates adverse currents when moved, hence, the scanning principle portrayed in Figure 30 is self-defeating. Another problem is that once an algal scum has passed into the skimmer and strikes the pump impellar, it is disrupted so that the feed to the secondary concentrator is to some extent homogenized with water and much wetter than it would be if no disruption occurred. This doubtlessly impairs the function of the skimmer to some extent. Although the system shown in Figure 34 can be made to work to some extent, it is far from the type of device needed for economical surface removal. The conception did serve however to yield data and point the way to a second generation skimming unit.

SPECIAL PROPERTIES OF FLOATING MICRO-ALGAE

Although secondary straining systems tested worked very well and it was assumed that good concentration factors could also be attained, the problem of pickup remained.

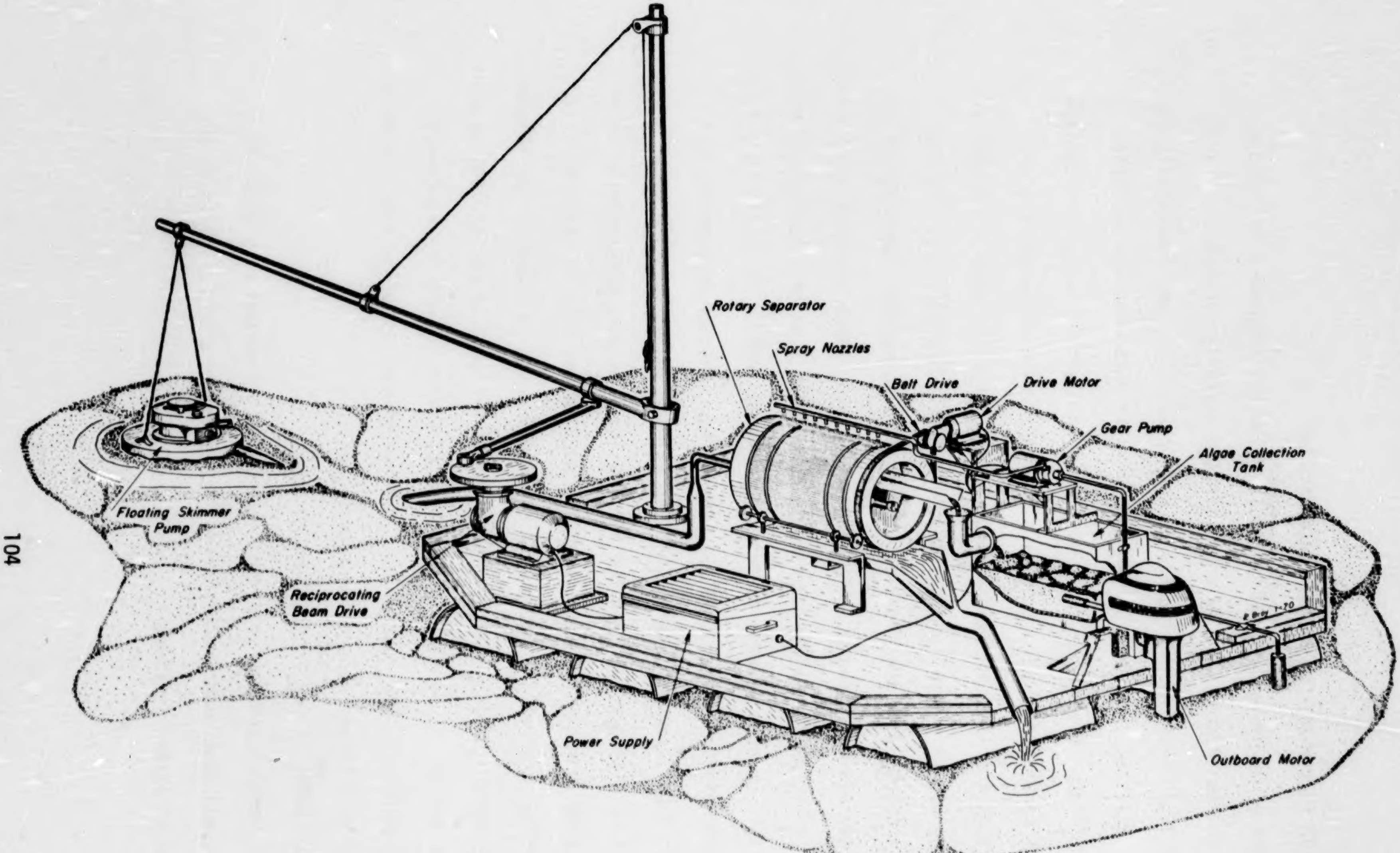

Rotary Separator
Spray Nozzles
Belt Drive
Drive Motor
Gear Pump
Algae Collection Tank
Floating Skimmer Pump
Reciprocating Beam Drive
Power Supply
Outboard Motor

FIGURE 34 Algae harvesting system

Crucial to the design of a pickup unit is information on the properties of the algae scum. There is a wealth of data in the literature on nutrients and nutrient growth interactions, and both DWR and Gaonkar's data amplified the information applied to Clear Lake. No data could be found, however, in the influence of floating algae on surface tension of the water supporting the floating algae. Preliminary studies were therefore made to determine the relationship between algal concentration and surface tension and the relationship between scum concentration and scum depth.

Studies with variable quantities of blue green algae as shown in Figure 35 indicate that there is a slight reduction in surface tension with increasing algal concentration. This relationship is shown for Oscillatoria and for Euglena. There is little question that the relationship also exists for Aphanizomenon, although the specific measurements for this algae remain to be made. The implications of the relationship above are apparent. As concentration increases, surface tension decreases, and the cells tend to be drawn together and cling to the surface. However, the energy differences are small and wind mixing easily breaks and disperses the layer of floating algae. In the presence of gentle winds however, the layer of algae tend to thicken and to pile up against the shore.

SCUM CONCENTRATION AND DEPTH

Experiments to determine the concentration-depth relations of natural algal scums was made in the "keys area" of Clear Lake under "serious bloom" conditions. The variation of scum concentration with location and depth is of interest in designing a pickup unit. This factor was measured by drawing suction samples from carefully gauged depths of existing scum layers with a vacuum pump and vacuum flask. Suction samples drawn into the vacuum flask were then subjected to routine solids determinations to

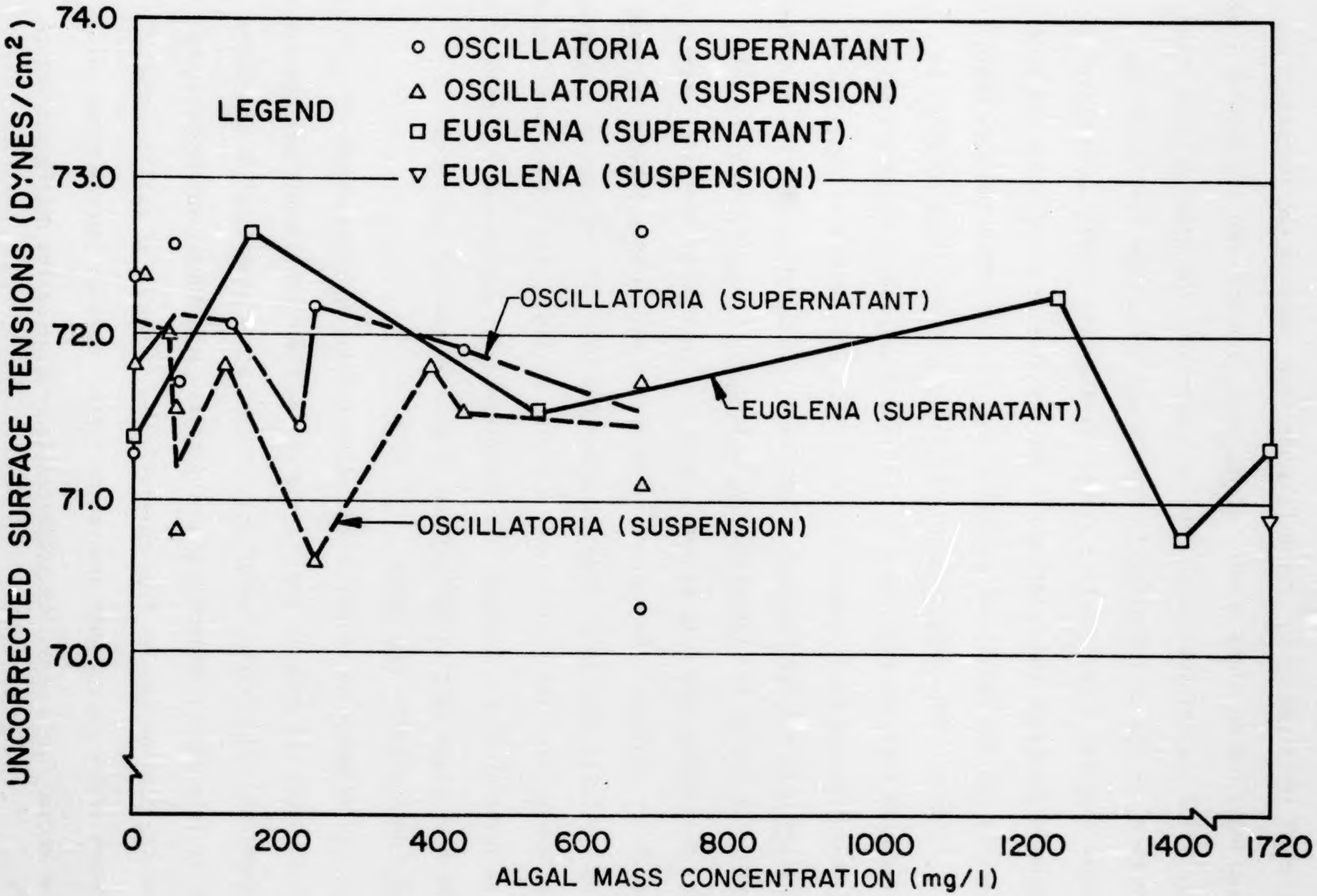


FIGURE 35 Surface tension vs algae mass concentration

determine the weights of algae involved. The general location of the area and a detailed map locating the specific sampling station is shown in Figure 36.

Results of these evaluations are tabulated in Table 24 and the data for "Motel Dock" are plotted in Figure 37. As is clear from Table 24 and Figure 37, the concentrations of algae, in the top layer or scum, exceeded by manyfold the assumed average maximum yield value of 19.3 for the lake and only approached the 19.3 value at the 6 and 12 inch depths. As shown in Table 24, the overall surface concentration factors, C_n, vary from about 100 on the lakeward side of the keys (Key No. 5) to 1,240 in the cul-de-sacs of Key No. 3. In spite of a "thick" superficial appearance, the algae scums proved to be relatively thin in vertical dimension, usually less than one centimeter in the case of relatively unconfined stations such as Key No. 5 , "Fire Station", "Lake Shore" and "Motel Dock" and 2 to 5 centimeters in depth in the confined ends of the canal and Key No. 3 where wind "jamming and folding" of the scum layer had obviously occurred.

Values for percentage of ash in the samples as a function of depth are also tabulated in Table 24 and plotted in Figure 37. The surface material, essentially pure Aphanizomenon, had an ash content of between 2.5 and 5% at all stations and in the case of "Lake Shore", "Key No. 3" and "Canal End", the ash content was between 3 and 5% in the top one-half inch; Key No. 5 at one-half inch depth had an ash content of 9%, and Fire Station and Motel Dock had ash contents of 23 to 32%. With the exception of Key No. 3, for which low ash material extended downward 4 inches, all stations evidenced a large fraction of fixed solids in samples from below 2 inches. Thus, much of the suspended material in the lake water from the various stations was comprised of extremely fine silt or clay in addition to algae.

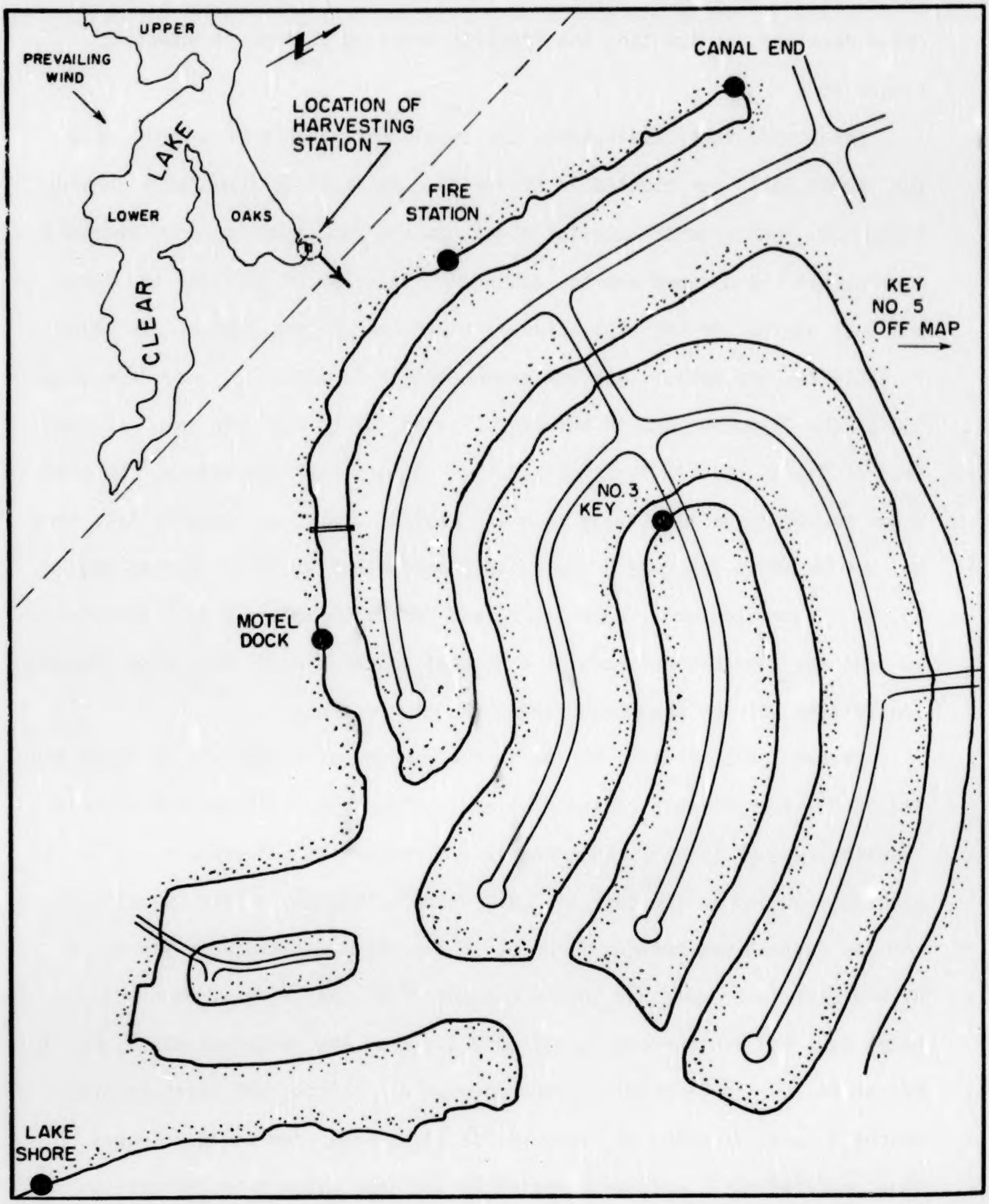

UPPER
PREVAILING WIND
LAKE
LOWER
OAKS
CLEAR
LOCATION OF HARVESTING STATION
CANAL END
FIRE STATION
KEY NO. 5 OFF MAP
NO. 3 KEY
MOTEL DOCK
LAKE SHORE

FIGURE 36 Lake sampling stations-location and designation

TABLE 24

CONCENTRATION OF BLUE-GREEN ALGAE IN CLEAR LAKE DUE TO NATURAL PROCESSES

Station	Depth cm	Suspended Solids mg/l			% Ash	C_n[a]	% Volatile
		Total	Vol, X_n	Ash			
Lake Shore	Surf	6,386	6,168	218	3.4	321.0	97.6
	1.3	114	109	5	4.4	5.6	96.4
	2.5	230	207	23	10.0	10.6	89.4
	5.1	73	62	11	15.0	3.2	85.0
	7.6	38	27	11	29.0	1.4	71.0
	10	61	45	16	26.4	2.3	73.6
	15	32	20	12	37.5	~ 1.0	62.5
	30	31	16	15	48.0	~ 1.0	52.0
Motel Dock	Surf	8,470	8,046	424	5.0	415.0	95.0
	1.3	85	65	20	23.4	3.4	76.6
	2.5	90	69	21	23.5	3.6	76.5
	5.1	51	28	23	45.0	1.4	55.0
	7.6	51	29	22	43.2	1.5	56.8
	10	39	18	21	54.0	~1.0	46.0
	15	42	19	23	55.0	~1.0	45.0
	30	49	17	32	65.0	~1.0	35.0
Fire Station	Surf	2,975	2,895	80	2.7	150.0	97.3
	1.3	68	49	19	28.0	2.5	72.0
	2.5	56	38	18	32.0	2.0	68.0
	5.1	56	26	30	54.0	1.3	46.0
	7.6	40	17	23	57.5	~1.0	42.5
	10	46	23	23	50.0	1.2	50.0
	15	46	20	26	57.0	~ 1.0	43.0
	30	45	18	27	60.0	~1.0	40.0
Canal End	Surf	15,930	15,055	875	5.5	823	94.5
	1.3	8,705	8,390	315	3.6	435	96.4
	2.5	4,050	3,820	230	5.7	198	94.3
	5.1	178	136	42	23.5	7.0	76.5
	7.6	106	59	47	44.2	3.0	55.8
	10	101	62	39	38.8	3.2	61.2
	15	78	45	33	42.2	2.3	57.8
	30	75	43	32	42.8	2.2	57.2
Key No. 3	Surf	24,700	24,000	700	2.9	1,240.0	97.1
	2.5	5,205	5,045	160	3.1	261.0	96.9
	5.1	308	296	12	3.9	15.3	96.1
	10	144	137	07	4.8	7.1	95.2
	15	122	109	13	10.6	5.7	89.4
	30	46	30	16	35.0	1.5	65.0
Key No. 5	Surf	1,975	1,925	50	2.5	100.0	97.5
	1.3	192	175	17	8.9	9.0	91.1
	2.5	88	72	16	18.3	3.7	81.7
	5.1	40	24	16	40.0	1.2	60.0
	30	34	20	14	41.5	~ 1.0	58.5

[a] Natural Concentration Factor for X_p = 19.3 mg/l

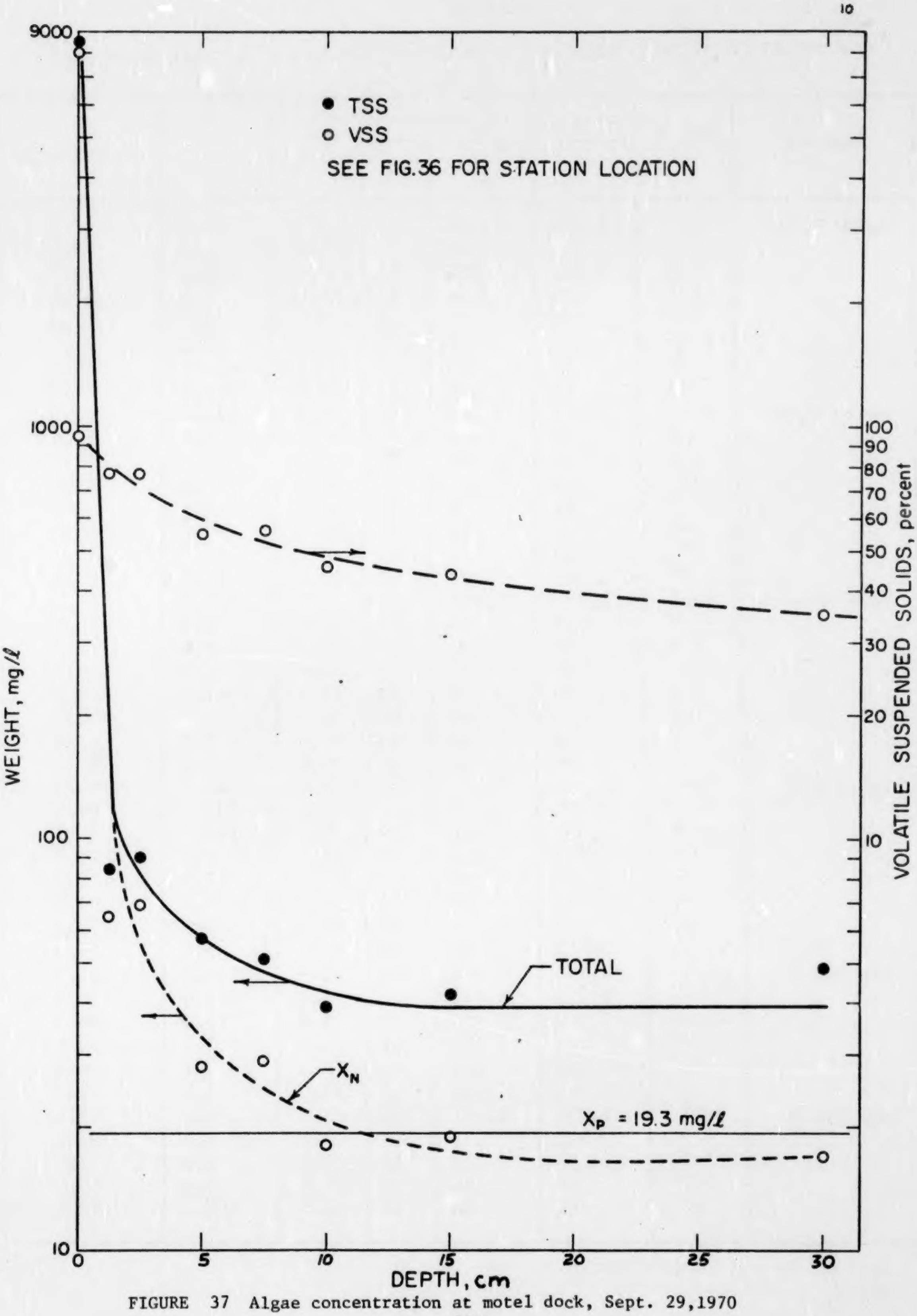


FIGURE 37 Algae concentration at motel dock, Sept. 29,1970

If one assumes that the volatile fraction was algae and the fixed fraction was silt, then the data indicates that more than 40% of the material below the surface scum was silt.

SEPARATION DEVICE NO. 2: DRAPER UNIT

On the basis of information on the nature of the algal scums and the need to have a mobile unit which could be moved into the scums, it was decided to construct a pickup system which had an endless belt comparable to the "drapers" on combined grain harvesters. Theoretically, the draper unit could be moved into and lift the scum layer from the surface and carry it upward past a doctor blade that would scrape the adhering material into a barge. A miniature draper unit was constructed and tested by manually applying it to algae scum. The scum was lifted by the miniature unit and consequently it was decided to construct a larger scale unit. A schematic diagram of the large scale unit is shown in Figure 38 and a photograph is shown in Figure 39.

A substantial effort went into design and construction of the draper unit. Because of work stoppage in the University shops due to a major university-wide trade strike, by the time the unit was ready for preliminary tests, there was a lack of harvestable scum. Also, the project funds had been depleted due to the extended time required to prepare for testing. It was therefore not possible to test the draper unit at Clear Lake. Inasumch as the project was entirely out of funds, all equipment was returned from Clear Lake to Richmond Field Station and the draper work was pursued by Mr. Sabanas on his own time. His effort was concentrated toward completing and testing the draper unit at Richmond. Fortunately, a floating algal scum had occurred as a result of overloading a one-quarter acre by seven-foot-deep experimental stabilization pond

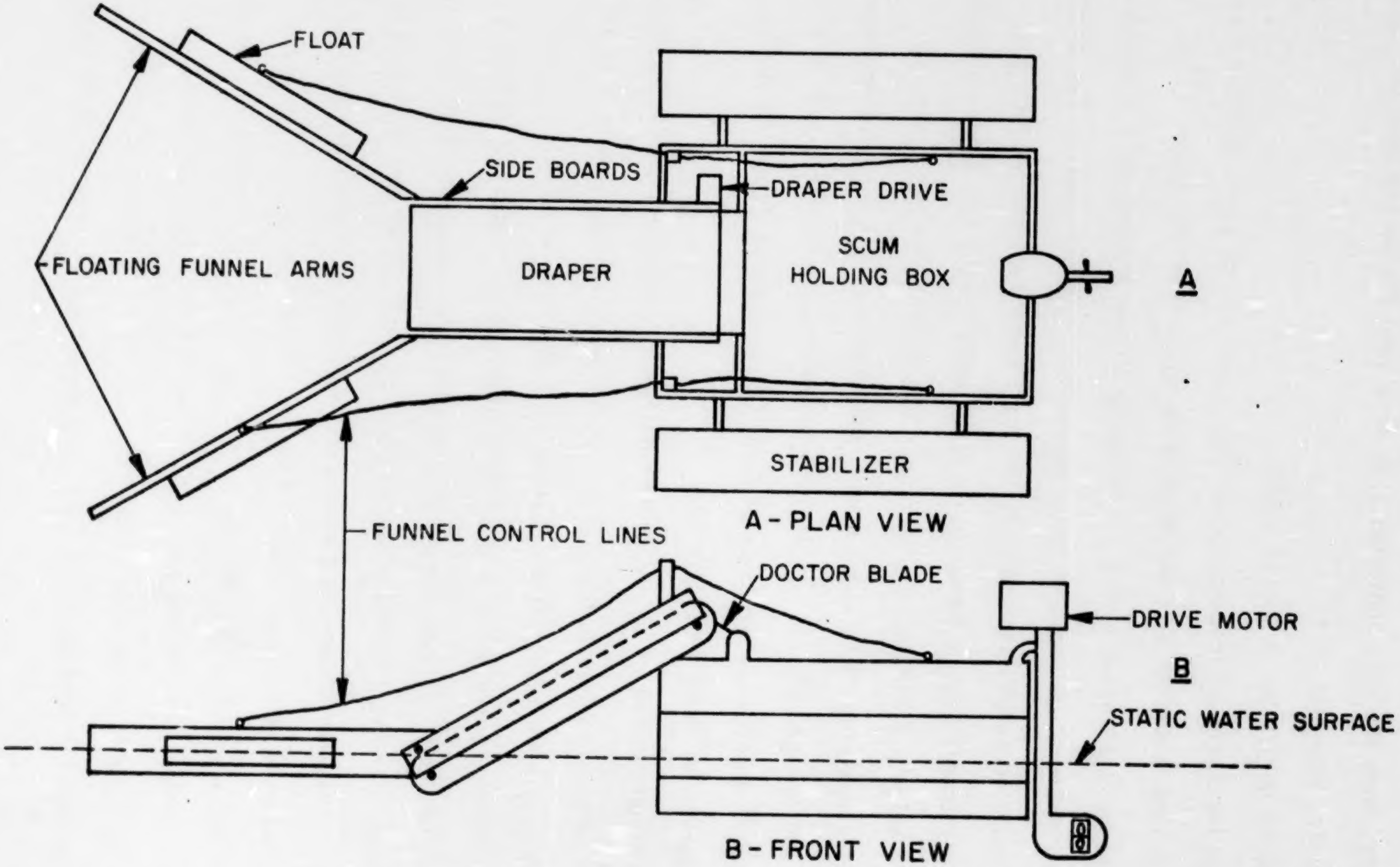

FLOAT
SIDE BOARDS
DRAPER DRIVE
SCUM
HOLDING BOX
FLOATING FUNNEL ARMS
DRAPER
A
STABILIZER
A - PLAN VIEW
FUNNEL CONTROL LINES
DOCTOR BLADE
DRIVE MOTOR
B
STATIC WATER SURFACE
B - FRONT VIEW

FIGURE 38 Schematic diagram of Draper Unit II

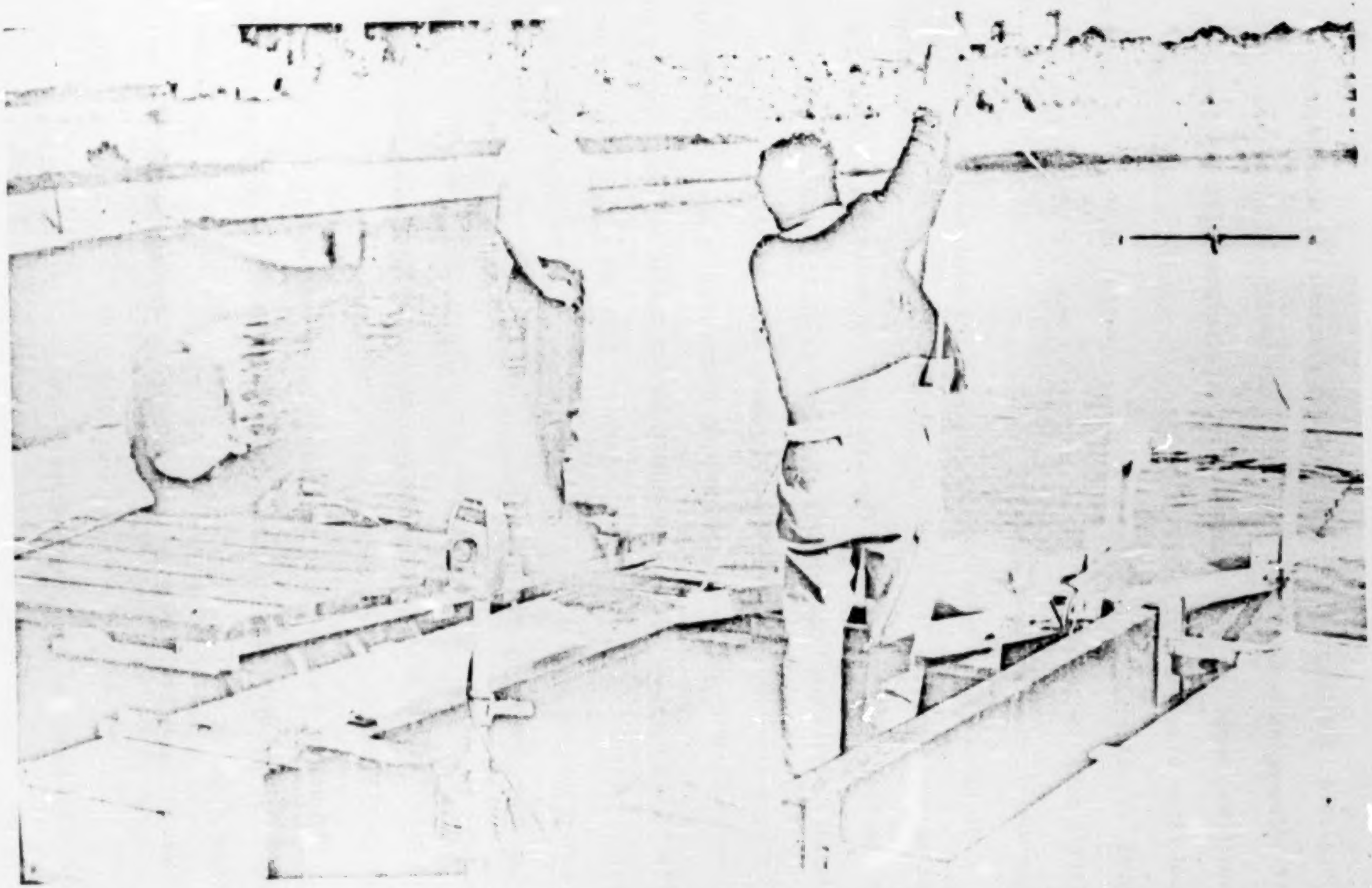


FIGURE 39 Photograph of full scale Draper Unit during testing at Richmond field station

located at the University Richmond Field Station. It was presumed that if encouraging results were found with the waste pond algal scum, funds would be sought so that studies could be attempted with Aphanizomenon and other blue green algae at Clear Lake or elsewhere. On the other hand, if discouraging results were found with pond algae, there could be little hope for better results with Aphanizomenon and other algae more hydrophilic than the pond algae.

In spite of the fact that studies with the miniature draper unit had been encouraging, the large draper unit did not perform satisfactorily on the floating algal scum on the waste pond at Richmond. Indeed, the floating scum showed no tendency at all to stick to the draper but instead, tended to slide off continuously and remain with the water. The pond algae thus exhibited highly hydrophilic properties in that it tended to stay with the water rather than adhere to the draper surface. During the test, a second major problem was observed. This was a hydraulic factor which interfered with algae pickup by a draper. In the tests there was a bow wave created by the draper-head as it was moved into the scum. This bow wave was of sufficient magnitude and velocity that hydrophilic algae were repelled and maintained in suspension rather than being "deposited out" on the beach-like draper surface.

One way of counteracting the "bow wave" effect would be to move the draper forward very slowly. Under low forward velocity experimental conditions, some of the floating material did tend to adhere to the draper and was lifted a bit. However, the velocity of forward motion required to obtain pickup was so slow that skimming of a significant area of a lake could not be accomplished in reasonable time.

A second hydraulic factor observed was that as the funnel arms moved forward, they tended to increase the depth of water in the funnel throat. This in turn produced a downward velocity to the throat water carrying the floating algae downward and beneath the unit rather than upward onto the draper. This observation made it obvious that hydraulic "jamming" cannot be applied to hydrophilic materials, but is only possible with materials such as oil which is hydrophobic and highly floatable.

Another problem that arose with the draper system was its cumbersome configuration. With funnel arms and the draper extending far out in front of the barge, the draper was not maneuverable. Because of its awkward shape and size, it would be confined to open water and useless in small coves and inlets where algal scums are most often found. In the open water, it would be vulnerable to physical damage by wind and wave action. Because of these obvious and apparently insurmountable difficulties, the draper system was abandoned as a mobile unit. It is possible that a system similar to the draper unit could be used effectively for fixed shore stations where algae would drift to the unit. Under these conditions, the "bow wave" problem would be eliminated and only the hydrophilic properties of the algae would be a problem. Although the draper unit itself was abandoned as a mobile unit, the information and experience gained with it permitted us to draw up specifications for a third pickup unit with none of the obvious disadvantages of the first and second units.

PICKUP UNIT NO. 3

Specifications for the third pickup system are as follows:

1. The layer of water containing or supporting the floating algae must be removed without distrubing underlying strata of water and with a minimum of head-loss. This means that partitioning of the surface scum

containing water should be done by a horizontal knife edge panel moving in such a way that there is a minimum of hydraulic disturbance at that point. The knife edge must therefore be out in front of any bow wave or disturbance caused by the unit. The blade should be able to pass below the water surface 0 to 7 centimeters.

2. The structure of the algal mat should undergo only minimal disturbance by the harvesting device and the floating algae should be captured completely within the device so that it cannot escape except by way of the secondary concentration system.

3. Although it should only be expected to be operational during quiescent periods which in the case of Clear Lake are normally early in the morning, the system should be capable of functioning when there are minor waves such as those produced by passing boats or the craft itself. It should therefore be stabilized by a very large float that is protected from small waves by a shroud. It should also be seaworthy so that there is no danger to the occupants or the craft in rough water.

4. Algal retraction or "float away" of algae should be impossible.

5. The unit should deliver algae to the concentrator with minimal amounts of conveyance water and therefore it should have provisions for excess water to "escape" from the unit leaving the algae behind inside the shroud. Thus, the unit should contain a primary screen.

6. The unit should be capable of operating in water that contains floating detritus without clogging or damage to the screens or pumps.

7. The unit should have an adjustable skimming depth so that scums of variable thickness can be captured.

8. The unit should be structurally strong and maneuverable.

9. The unit should be large enough to have hydraulic similitude with functional units. Thus, any prototype units should have a minimum length of 3.7 meters and a minimum width of 1.2 meters and minimum depth of 0.6 meters.

A schematic diagram of a pickup device which embodies each of these design features is shown in Figure 40. Conceptually the unit depicted in Figure 40 operates by being moved forward into the algal scum layer. The "skim lip" slides beneath the algal layer with minimum surface disturbance. Algae are trapped within the shroud and moved backward over a #250 mesh screen where most of the water escapes leaving the algae suspended in new water as it continuously enters with suspended algae. When the screen becomes slightly clogged, the water level rises slightly around the polymer float. The rise in water surface will activate a switch which will turn on the scavenger pump. As the pump discharges, lake water will be drawn upward through the screen dislodging algae and cleaning the screen. Normally it should not be necessary to stop the forward motion of the system during the backwashing.

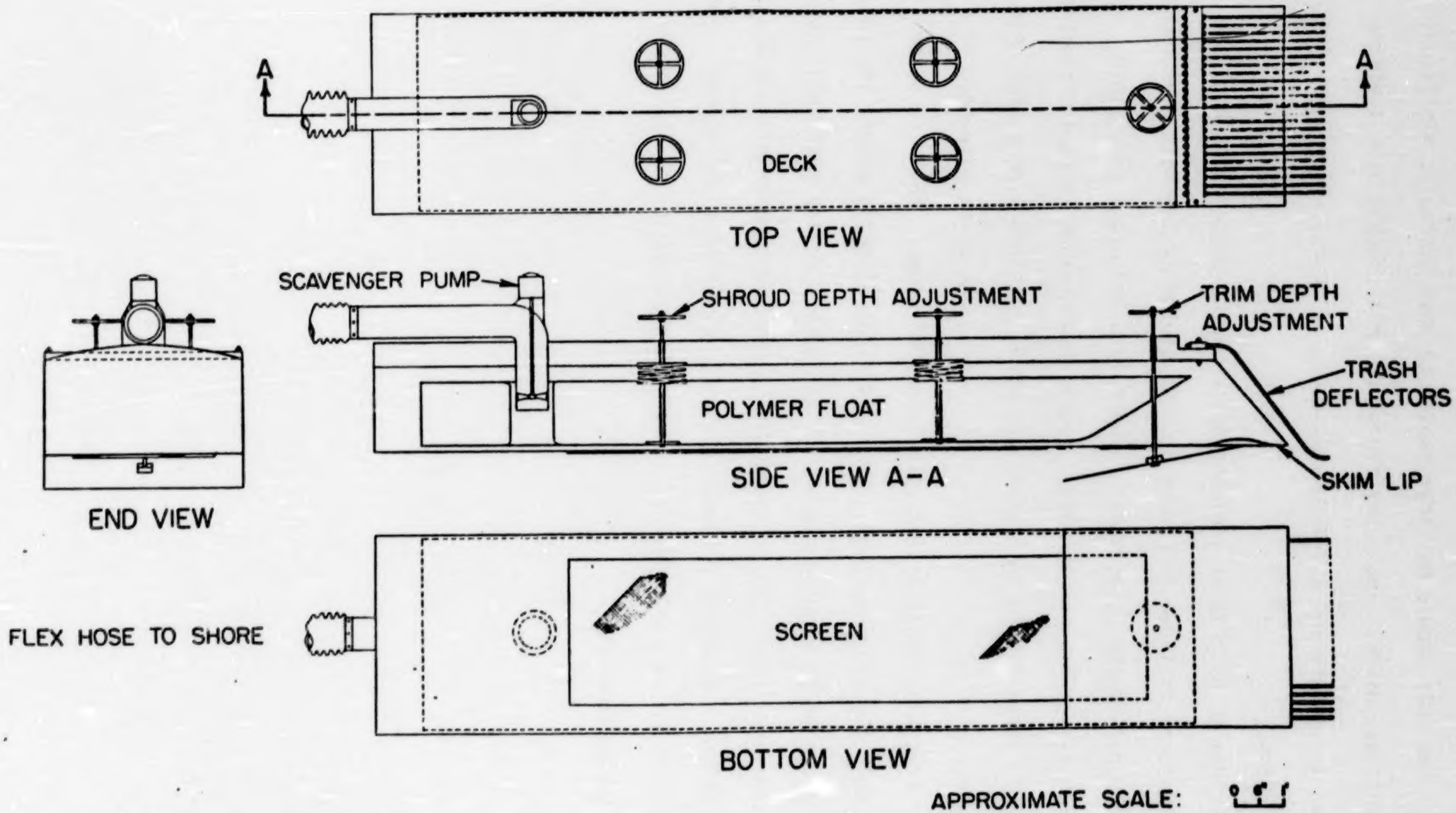

A
A
DECK
TOP VIEW
SCAVENGER PUMP
SHROUD DEPTH ADJUSTMENT
TRIM DEPTH ADJUSTMENT
TRASH DEFLECTORS
POLYMER FLOAT
SKIM LIP
SIDE VIEW A-A
END VIEW
FLEX HOSE TO SHORE
SCREEN
BOTTOM VIEW
APPROXIMATE SCALE:

FIGURE 40 Conceptual drawing of U.C. surface skimming device for suspended micro-algae

SECTION V.

OVERALL SYSTEMS FOR HARVESTING, CONCENTRATION, DRYING, AND DISPOSAL

If the mobile pickup unit proves functional, it will be possible to operate the overall systems shown in Figure 41 at each harvesting station.

In configuration 1 of Figure 41, the mobile pickup discharges through a floating flex hose into a rotary microstrainer which is mounted on a semi-fixed barge located in the vicinity of the skimming operation. The barge itself may further act as a decanter where additional algal free water may be withdrawn. Periodically the contents of the barge are discharged onto prepared sandbeds where the algae dry and form chips which later can be collected for disposal or use. As indicated in configuration 2 and 2A, in local areas of the lake where scum frequently collects, it may be feasible to dispense with the barge and pump the concentrate directly to a shore bound rotary strainer and thence either into an anaerobic fermenter for extraction of energy in the form of methane gas, or onto sand beds for drying.

Mechanical drying of algae costs approximately five cents per pound and would only be feasible if the algae were to prove unusually valuable as a source of pharmaceuticals or other valuable by-products.

In order to make an economic analysis of the overall system depicted in Figures 40 and 41, it is essential to develop crude algorithms for the pickup unit and for the entire system. These will be developed in terms of the size, depth and speed of the unit, areas to be harvested, volumes of liquid processed, primary and secondary concentration factors attainable, and sand bed areas required.

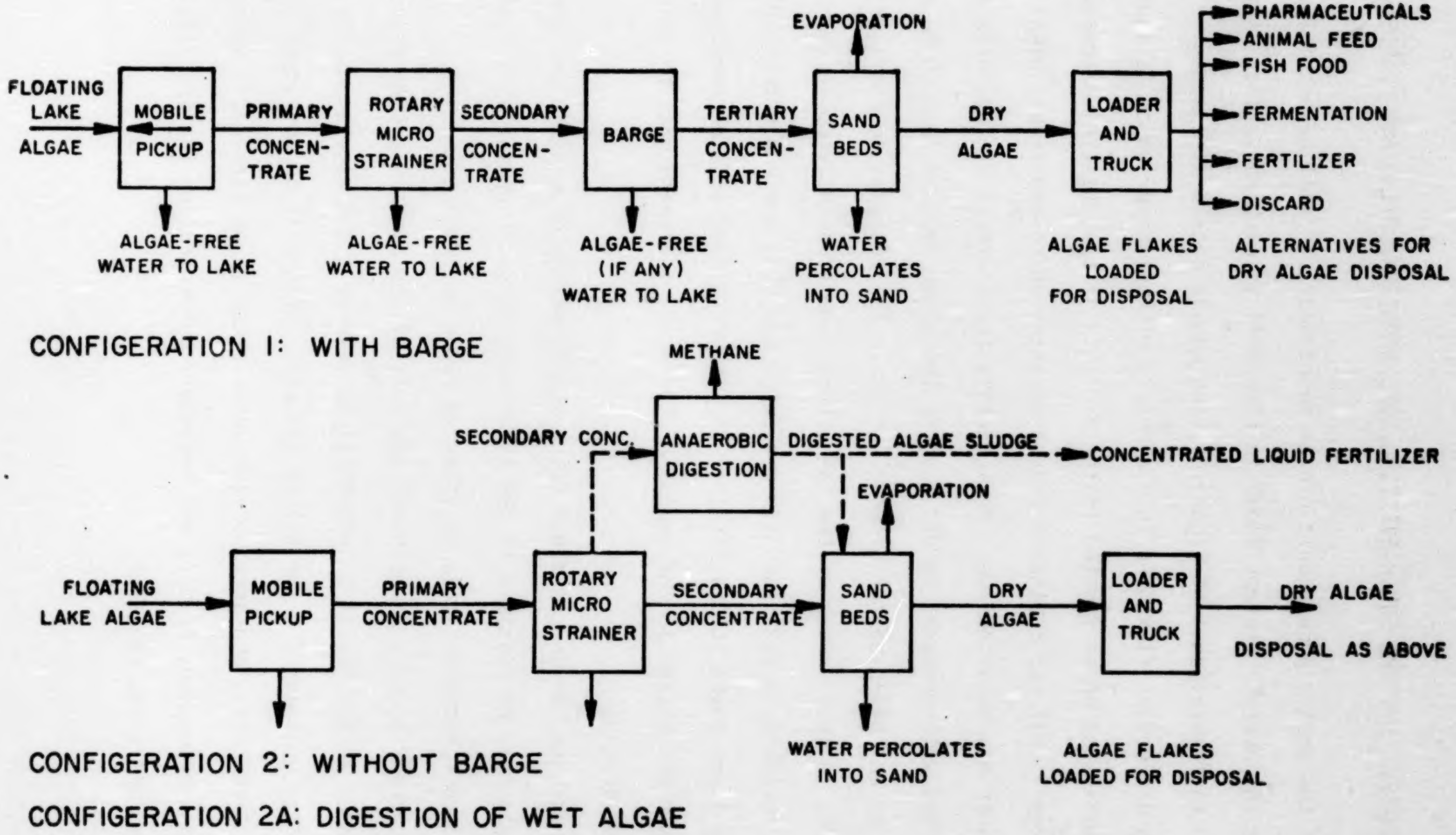

FLOATING LAKE ALGAE
MOBILE PICKUP
PRIMARY CONCENTRATE
ROTARY MICRO STRAINER
SECONDARY CONCENTRATE
BARGE
TERTIARY CONCENTRATE
SAND BEDS
EVAPORATION
DRY ALGAE
LOADER AND TRUCK
PHARMACEUTICALS
ANIMAL FEED
FISH FOOD
FERMENTATION
FERTILIZER
DISCARD
ALGAE-FREE WATER TO LAKE
ALGAE-FREE WATER TO LAKE
ALGAE-FREE (IF ANY) WATER TO LAKE
WATER PERCOLATES INTO SAND
ALGAE FLAKES LOADED FOR DISPOSAL
ALTERNATIVES FOR DRY ALGAE DISPOSAL
CONFIGERATION 1: WITH BARGE
METHANE
SECONDARY CONC.
ANAEROBIC DIGESTION
DIGESTED ALGAE SLUDGE
CONCENTRATED LIQUID FERTILIZER
EVAPORATION
FLOATING LAKE ALGAE
MOBILE PICKUP
PRIMARY CONCENTRATE
ROTARY MICRO STRAINER
SECONDARY CONCENTRATE
SAND BEDS
DRY ALGAE
LOADER AND TRUCK
DRY ALGAE
DISPOSAL AS ABOVE
WATER PERCOLATES INTO SAND
ALGAE FLAKES LOADED FOR DISPOSAL
CONFIGERATION 2: WITHOUT BARGE
CONFIGERATION 2A: DIGESTION OF WET ALGAE

FIGURE 41 Harvesting systems for surface micro-algae

INTERCEPTION WIDTH, DEPTH, VELOCITY AND VOLUME

Let w equal the width of the leading or intercepting edge of the harvesting device, let d equal the depth of the intercepting edge of the harvesting device, and let v equal the forward velocity of the harvesting device. If w is expressed in meters, d in centimeters; and v in centimeters per sec, then

$$V = \frac{wdv}{10} \qquad (3)$$

in which V is the volume intercepted or harvested in liters per second. Similarly by continuity

$$A = \frac{wv}{100} \qquad (4)$$

in which A is the area harvested in square meters per second.

On the basis of our experimental work we can assign a range of numerical values of each of the above physical dimensions for the harvesting systems in Figure 29.

It is apparent that values of w less than 1.5 meters would be too small to permit coverage of much area in a day. On the other hand, a width greater than 7.6 meters would be extremely unwieldy. Hence, 7.6 meters is the maximum width to be considered.

INTERCEPTION DEPTH

As indicated in Table 24, scum formations involve depths of material that normally do not exceed 5 centimeters and usually do not exceed 1 centimeter. Moreover, harvesting should be carried out before a scum layer of more than 1 centimeter forms. On the other hand, if scum buildup were fast and wind jamming intense, scums as thick as 5 centimeters could develop. Accordingly, a maximum harvesting depth would be about 5 centimeters.

With regard to minimum depth, it is unlikely that any device can be effectively operated at depths less than 0.6 centimeters.

INTERCEPTION VELOCITY

Interception velocities from 15 centimeters per second to 150 centimeters per second (0.6 to 5.5 kilometers per hour) should be considered. The lower velocity is arbitrary -- the higher to limit turbulence and wave action that would occur and disrupt parts of the scum-field not being harvested.

UNIT PROCESS RATES

Based on the above ranges of values for width, depth and volume, it is evident that the minimum process volume to be considered using Equation 3 is 1.5 x 0.6 x 15 ÷ 10 = 1.4 liters/sec and the maximum 7.6 x 5 x 150 ÷ 10 = 570 liters/sec. These and intermediate values are tabulated in Table 25.

Similarly, based on the ranges of values for depth and velocity, it is evident from Equation 4 that the minimum rate of lake surface processed is 1.5 x 15 ÷ 100 = 0.2 m^2/sec and the maximum 11.6 m^2/sec. These values are equivalent to about 0.09 hectares per hour and 4.2 hectares per hour, respectively. These and all intermediate values are shown in Table 26. To use Table 26, enter with the pickup width and velocity and obtain the area harvested in hectares. Assuming 6 hours per day of steady-state harvesting at 150 cm per second, the areas covered would be 5.0 hectares per day and 27.5 hectares per day for a 1.5 meter and a 7.6 meter pickup unit, respectively.

TABLE 25

VOLUMES HARVESTED IN LITERS PER SECOND[a] FOR VARIOUS WIDTHS, DEPTHS AND VELOCITIES OF THE INTERCEPTING ELEMENT

W m	D cm	Forward Velocity	Upper Line: Centimeters per Second Lower Line: Kilometers per Hour			
		.15	49	84	118	152
		.55	1.79	3.03	4.27	5.47
1.5	.61	1.4	4.6	7.8	11.0	14.2
1.5	1.68	3.9	12.6	21.4	30.3	38.8
1.5	2.74	6.4	20.7	35.1	49.2	63.7
1.5	3.81	8.8	28.9	48.7	68.5	88.6
1.5	4.88	11.3	36.5	62.3	87.7	113
3.1	.61	2.8	9.2	15.6	21.9	28.3
3.1	1.68	7.8	25.2	42.7	60.3	77.8
3.1	2.74	12.7	41.3	69.9	98.5	127
3.1	3.81	17.7	57.4	97.4	137	177
3.1	4.88	22.6	73.3	125	175	226
4.6	.61	4.2	13.7	23.3	32.8	42.4
4.6	1.68	11.7	37.9	64.5	90.8	117
4.6	2.74	19.1	61.7	105	148	191
4.6	3.81	26.6	86.0	146	206	266
4.6	4.88	34.0	110	187	263	340
6.1	.61	5.7	18.4	31.1	43.9	56.6
6.1	1.68	15.6	50.4	85.7	121	156
6.1	2.74	25.5	79.8	140	198	255
6.1	3.81	35.4	115	194	275	354
6.1	4.88	45.3	147	250	351	453
7.6	.61	7.1	23.2	39.1	55.2	70.8
7.6	1.68	19.5	63.1	107	151	195
7.6	2.74	31.7	103	175	247	317
7.6	3.81	44.1	143	243	317	441
7.6	4.88	56.5	184	311	439	566

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[a] To convert liters per second to cubic feet per second, divide by 28.3.

AREAS TO BE HARVESTED

The total area of Clear Lake (A_1) is 17,700 hectares, but removable concentrations of algae do not normally cover more than a fraction of the surface of the lake. To estimate the fraction requiring skimming, we have measured the values of X_p which are given in Table 15 and we have measured natural concentration factors "C_n" which are given in Table 24. With these data, we can estimate the area of a Lake's surface, which must be skimmed, A_s, as follows:

$$\frac{A_s}{A_1} = \frac{X_p}{X_n} \tag{5a}$$

in which X_n is the dry weight of naturally concentrated algae in a scum layer in mg/l and X_p is the maximum growth potential as defined in Equation 2a.

If Equation 5a is solved for A_s, one obtains

$$A_s = \frac{X_p}{X_n} A_1 \tag{5b}$$

or

$$A_s = \frac{A_1}{C_n} \tag{5c}$$

in which C_n is the natural concentration factor.

Smaller areas than predicted by Equations 5b and 5c may require skimming but it is unlikely that greater areas will require skimming because there simply is no source for more algae to be produced quickly.

To visualize the areas involved, consider the smallest concentration factor observed in Table 24. The factor was $C_n = 100$. If we substitute $C_n = 100$ in Equation 5c, we obtain the following

$$A_s = \frac{17,700}{100} = 177 \text{ hectares}$$

On the other hand if one substitutes the largest value of C_n, 1240, obtained in Table 24, one has only

$$A_s = \frac{17,700}{1,240} = 14.3 \text{ hectares}$$

To be conservative equipment designs should be based on the largest conceivable area to be harvested several times in a season.

HARVESTER SIZE

According to Table 26, a 1.5 meter harvester moving 150 centimeters per second can harvest 0.8 hectares per hour or 4.9 hectares per six hour day (two hours allowed for adjustments or repairs). To harvest 177 hectares would require 177/4.9 = 36 days. Thus, all of the area could be covered twice and part of it three times in a ninety day season. If a 7.6 meter harvester were used, only six days would be required to cover 177 hectares. On the other hand, the larger harvester would be awkward to use around small bays or keys whereas the smaller unit would be more manageable. It would therefore seem more reasonable to initially operate a 1.5 meter unit until experience is gained, after which different size units could be utilized depending on need.

CONCENTRATION FACTORS

Without experimental data on operational skimming machines, it is not possible to predict the concentration factors to be attained with the primary pickup unit. Preliminary experiments with a 250 mesh screen indicated that one could operate for one minute at 6.8 liters/m^2/sec in a 100 mg/l concentration before a head loss of 5 cm developed. Backwash was accomplished at 6.8 liters per square meter per second for two seconds. The indicated concentration factor is 30:1. On this basis it is felt that in thick, 1000 mg/l slurries, concentration factors of 10:1 can be safely

TABLE 26

HARVESTED AREA AS A FUNCTION OF HARVESTER VELOCITY AND WIDTH

Harvester Width	VELOCITY OF MOVEMENT OF HARVESTER IN CENTIMETERS PER SECOND									
	15.2		49.4		83.9		118		152	
	Area		Area		Area		Area		Area	
m	m^2-sec^{-1}	ha-hr^{-1}	m^2-sec^{-1}	ha-hr^{-1}	m^2-Sec^{-1}	ha-hr^{-1}	m^2 Sec^{-1}	ha-hr^{-1}	m^2-Sec^{-1}	ha-hr^{-1}
1.52	0.23	0.08	0.75	0.27	1.28	0.46	1.80	0.65	2.32	0.84
3.05	0.46	1.17	1.50	0.54	2.55	0.92	3.60	1.30	4.64	1.67
4.57	0.70	0.25	2.26	0.81	3.84	1.38	5.41	1.95	6.97	2.51
6.10	0.93	0.33	3.01	1.08	5.11	1.84	7.21	2.60	9.29	3.34
7.62	1.16	0.42	3.76	1.35	6.39	2.30	9.01	3.24	11.6	4.18

expected and in thinner slurries, concentration factors of 20:1.

Accordingly, the assumed primary concentration factors will be taken at 10:1 for thick slurries and 20:1 for thin slurries.

The concentrations attainable in rotary microstrainers are somewhat better known. Our experiments (see Table 22) with a very small rotary straining unit indicate concentration factors of 25:1 at about 2.8 liters per sec on a 250 mesh x 0.5 m^2 unit. Removal was only 32%. Lower concentration factors were attained at higher rates and surprisingly, removal improved, but the unit was filtering through less than 10 percent of the potential filtration area. Presumably if a larger surface contact area were provided, greater volumes of liquid could be passed at lower rates with better removal efficiency. For purposes of our cost calculations, it will be presumed that concentration factors of 10:1 can be attained through a microstrainer with a flow rate of 34 liters/m^2/sec.

ALGAE DRYING AREAS

As noted previously, it is envisaged that the algal slurry concentrated through the system would be placed on sand beds for dewatering and drying. The methodology for using sand beds for dewatering algae has been worked out previously and described by Oswald and Golueke(1). It does not seem likely that any significant unforeseen problems will arise in this part of the process. On a sand bed, the water will seep or evaporate away leaving a layer of moist algae about 2 cm thick. This layer of algae shrinks and cracks as it drys. The flakes then curl and dry completely and can be easily removed with a loader. Experience indicates that the total time on a sand bed from spreading until the algae can be removed with a loader will not exceed two weeks. Accordingly, sufficient bed area must be available for two weeks accumulation of slurry at say 57,000 liters per day. The total bed volume for two five day weeks is 610,000 liters. Maximum spreading depth is 15 cm hence, 0.4 hectares of bed would be required for each unit. This should be divided into 10 beds with each bed 370 m^2 in area. Allowing for access roads and equipment storage, a 0.8 hectare drying site would be ideal for each 61,000 liters per day of slurry to be dried. Inasmuch as all slurry will not be harvested and dried prior to November 1 of each year it is possible that an October rainfall will occasionally disrupt the drying process. Summer thunderstorms could also be disrupting. Experience indicates that one rewetting of the algae will lead to little odor provided drying proceeds again within a few days. Repeated wettings will lead to odor and should be avoided.

OPERATIONAL PARAMETERS

A summary of operational parameters for two sizes of systems is presented in Table 27. In Table 27, it is assumed that the 1.5 meter units can operate close to shore in thickened algal scums, whereas the more awkward 7.6 meter unit would have to stay well out in the lake where algal scums are not always as thick as desirable for best harvesting. The concentrations of algae assumed at the surface are conservative compared with concentrations of several thousand mg/l evidenced in Table 24. On the other hand, if a skimming program is working, it will not normally be feasible to wait for surface concentrations much greater than 100 mg/l

In the case of surface skimming as a method of removing nutrients from natural bodies of water, it will probably be necessary to apply units much larger than the 1.5 meter units proposed for skimming the margins of Clear Lake. Because of their size, these large units would have to operate in more open parts of the lake and would consequently process more

TABLE 27

SUMMARY OF OPERATIONAL PARAMETERS FOR TWO SIZES OF ALGAL SKIMMING UNIT

Item no.	Item	Unit Size	
1.	Size of Unit, meters of width	1.52	7.62
2.	Size of Base Screen, m^2	3.72	37.2
3.	Volume Processed @1.5m/sec, 5 cm depth, liters/sec	113	566
4.	Screen Velocity, liters/m^2/sec	31	15
5.	Primary Concentration Factor	5:1	20:1
6.	Volume Processed, liters/sec	110	570
7a	Volume of Primary Concentrate, liters/sec	23	28
7b	Volume of Primary Concentrate, liters/6 hr day	81,800	102,000
8.	Secondary Concentration Factor	10:1	10:1
9a	Volume of Secondary Concentrate, liters/sec	2.3	2.8
9b	Volume of Secondary Concentrate, liters/6 hr day	50,000	61,000
10.	Operating Input Concentration, mg/l	1,000	200
11.	Primary Concentrate Concentration, mg/l	5,000	400
12.	Secondary Concentrate Concentration, mg/l	50,000	40,000
13.	Weight of Algae per day, kilograms	2,400	2,400
14.	Weight of Algae per day, metric tons (MT)	2.4	2.4
15.	Weight of Algae per 90 days, MT	220	220

water with concentrations of algae much lower than would be available to smaller units. The volumes of water to be processed would be much greater but the attainable concentration factor through the screen would not be much greater so that the total concentrate processed would be about the same as that of a 1.5 meter unit. Under ideal circumstances a 7.6 meter unit operating for 90 days at 6 hours per day would be able to process 12.5 percent of the surface area of Clear Lake and could operate in surface concentrations as low as 100 mg/l. However, the amount of algae produced could be as little as 1.5% of the total biomass of 14,000 metric tons of algae estimated to be in the lake.

SECTION VI

ECONOMIC ANALYSIS

COST OF SKIMMING STATIONS

In Tables 28 and 29, unit costs are estimated for the two sizes of skimming stations. It is estimated that the cost of one 1.5 meter skimming station will be $50,000 (1974 dollars) per year including interest, amortization, operating, maintenance and insurance.

BENEFITS

Substantial benefits will accrue to Clear Lake if the algae scum problem can be solved. These benefits would appear in the form of property value improvement and in increased visitor days. There also may be benefits from selling the algae produced. A summary of estimated benefits without algae sales is given in Table 30A. A summary of estimated benefits with algae sales is given in Table 30B.

BENEFIT COST RATIO FOR SCUM REMOVAL

A benefit cost comparison for scum removal is given in Table 31. Apparently, from the data in Table 31, benefit cost ratio is high and it will be singularly beneficial to the lake to remove the algae from it. However, it should be emphasized that the entire project is dependent upon the performance of an as yet untested surface algae pickup unit. A question might also arise regarding the need for multiple stations. It appears that up to three stations could be built and still maintain a benefit cost ratio greater than 1.0 without algal sales. With algal sales, the benefit cost ratios are higher.

TABLE 28

COST ESTIMATES FOR ONE 1.5 METER ALGAE PICKUP UNIT AND SUPPORTING SYSTEM, OPERATING 90 DAYS PER YEAR

Capital Cost per Station	Est. Cost 1974 $
1.5 meter Pickup Unit and Equipment	20,000
30,000 liter Barge	15,000
Sabanas Portable Microstrainer (28 liters/sec)	10,000
Leveling and Preparation of 0.8 hectares of Sand Beds	30,000
Algae Loader	10,000
Electrical Pumps and Motors	10,000
Subtotal	95,000
Engineering @ 12.5%	12,000
Contingency @ 15%	15,000
Grand Total	$122,000
Annual Costs for One 1.5 Meter Skimming Station	
Amortization and Interest on Capital (15% per annum)	18,000
Rental of Sand Beds	5,000
Insurance	2,000
Fuel and Electricity	4,000
3 Men (4 man months each)	15,000
Miscellaneous Supplies & Equipment	4,000
Administration	2,000
Total Annual Cost	$50,000

TABLE 29

COST ESTIMATES FOR ONE 7.6 METER ALGAE PICKUP UNIT AND SUPPORTING SYSTEM, OPERATING 90 DAYS PER YEAR

Capital Cost per Station	Est. Cost 1974 $
7.6 meter Pickup Unit and Equipment	55,000
30,000 liter Barge	15,000
Sabanas Portable Microstrainer (28 liters/sec)	10,000
Leveling and Preparation of 0.8 hectares of Sand Beds	30,000
Algae Loader	10,000
Electrical Pumps and Motors	10,000
Subtotal	130,000
Engineering @ 10%	15,000
Contingency @ 15%	20,000
Grand Total	$163,000
Annual Costs for One 7.6 meter Skimming Station	
Amortization and Interest on Capital (15% per annum)	25,000
Rental of Sand Beds	5,000
Insurance	2,000
Fuel and Electricity	6,000
3 Men (4 Man months each)	15,000
Miscellaneous Supplies & Equipment	5,000
Administration	3,000
Total Annual Cost	$63,000

TABLE 30A

ESTIMATE OF ANNUAL BENEFITS RESULTING FROM ALGAE SKIMMING PROGRAM BASED ON ONE MOBILE STATION WITHOUT ALGAE SALES

Item and Basis	Value 1974 $
1. Property Improvement:	
Value of property $300 per lake front foot. Lake front in private ownership is 300,000'. Total Value: $90,000,000. Assume only front 10% affected and 1% appreciation of property	90,000
2. Increased Visitor Days:	
Assume current visitor days = 200,000 per year at $5 per day. Current visitor day value: 200,000 x 5 = $1,000,000. With correction of floating algae problem, visitor days should increase 10%.	100,000
TOTAL VALUE OF BENEFITS	$190,000

TABLE 30B

ESTIMATE OF ANNUAL BENEFITS RESULTING FROM ALGAE SKIMMING PROGRAM BASED ON ONE MOBILE STATION WITH ALGAE SALES

Item and Basis	Value 1974 $
1. Potential Values of Harvested Algae:	
220 Metric Tons @ $100/MT	22,000
660 " " "	66,000
2200 " " "	220,000

TABLE 31

BENEFIT COST RATIOS FOR SCUM REMOVAL

	One 1.5 meter unit 1974 $	One 7.6 meter unit 1974 $
1. WITHOUT ALGAE SALES		
Annual Cost of Stations	50,000	63,000
Cost of Algae Disposal	2,200	2,200
Total Cost	52,200	65,200
Annual Benefits from Skimming without Algae Sales	190,000	190,000
Benefit Cost Ratio without Algae Sales	3.60	2.91
2. WITH ALGAE SALES AT 220 METRIC TONS		
Annual Cost of Stations	50,000	63,000
Cost of Algae Marketing @ $5.00 per MT	1,100	1,100
Total Cost	51,100	64,100
Annual Benefit from Skimming with Algae Sales	212,000	212,000
Benefit Cost Ratio with Algae Sales @ 220 MT	4.14	3.31
3. WITH ALGAE SALES AT 2,200 METRIC TONS		
Annual Cost of Stations	50,000	63,000
Cost of Marketing Algae @ $5.00 per MT	1,100	11,100
Total Cost	61,000	74,000
Annual Benefit from Skimming with Algae Sales	410,000	410,000
Benefit Cost Ratio with Algae Sales @ 2,200 MT	6.72	5.54

BENEFIT COST RATIO FOR NUTRIENT REMOVAL

The benefit cost ratio for nutrient removal alone is not particularly favorable without algal sales. If only 220 metric tons of algae per year are obtained from a station, the cost of algae from the 1.5 meter pickup unit will be $227 per ton and the cost of algae from the 7.6 meter unit will be $286 per ton. If the algae harvested are 8 percent nitrogen and 1 percent phosphorus it would be $2.80 to $3.60 per kilogram nitrogen or $22.70 to $28.60 per kilogram phosphorus. On the other hand, if 2,200 tons of algae per year are obtained from the station, costs would be roughly 1/10 as much. Accordingly the sale of algae for $100 per metric ton could yield a profit. The "break even" point at which algae sales can offset the cost of removal would be a yield of about 550 tons for a 1.5 meter unit and 660 tons for a 7.6 meter unit.

If the algae could be sold for more than $100 per metric ton, nutrient removal costs would decline proportionally. While it is speculative to ascribe any value to algae, it should be noted that a blue-green algae is currently being harvested from Lake Texcoco in Mexico and is being sold for $2.00 per kilogram or $2000 per metric ton. Thus a value of $100 per ton seems conservative. It would also be beneficial from a unit cost standpoint if greater amounts of algae could be obtained while skimming is in progress. It is hoped, however, that concentrations would eventually decline since this would indicate the achievement of better control of surface algal concentrations and possibly "de-eutrophication" of a eutrophic lake.

SECTION VII

FUTURE WORK

The most essential part of this project for the future is to build and test the algae pickup device shown in Figure 40. Without a suitable pickup device, other aspects of the project cannot be completed and would simply be inapplicable. Because this fact was realized as the project neared the end of its second year, and because our federal funds had been depleted by the interminable but unavoidable delays and adversities described herein, the Clear Lake Council had expressed a strong interest in granting funds for building and testing the new pickup element at an early time. We have not requested additional federal funds because it was hoped that testing of the technical feasibility of the pickup device in Figure 40 could be completed with supplementary grant funds from the Lake County Board of Supervisors so that any new request for federal funds could be drawn up as a demonstration type project instead of a continued search for a pickup device.

Administrative difficulties have however delayed receipt of the funds from the Lake County Board and it has therefore become necessary to terminate the Federal Project short of a clear solution of the problem of a pickup device. In the event Lake County funds do become available and the pickup device shown in Figure 40 can be built and tested, a supplementary report will be filed with the Northwest Water Laboratory of EPA giving the results of our tests with the pickup device.

SECTION VIII

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The late Mr. Mitchell Sabanas, Senior Laboratory Mechanician of the Sanitary Engineering Research Laboratory of the University was with the project from its inception until his fatal heart attack giving freely of his personal time during the many problems which arose as the project progressed.

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